PLASTIC WORKING
OF METALS AND NON-METALLIC MATERIALS
IN PRESSES

BY

E. V. CRANE, Ph.B., M.E.

THIRD EDITION

Fourth Printing

NEW YORK
JOHN WILEY & SONS, INC.
CHAPMAN & HALL, LTD.
LONDON

THIRD EDITION

Fourth Printing, September, 1948

PRINTED IN THE UNITED STATES OF AMERICA

PREFACE TO THE THIRD EDITION

Recognition of the several states of plasticity makes it possible to show that the press working methods of mass production follow rather simple rules throughout the expanding range of engineering materials. Such groupings as metallic, organic and ceramic merge into a common problem in parts production. Many of the chemical elements are synthesized, alloyed or otherwise grouped together in many ways for commercial utility. Large numbers of the materials so formed are plastically workable and reworkable in the *crystoplastic, soluplastic* or *thermoplastic* states. Other combinations enjoy brief mobility in process through the chemical change of the *thermosetting* or *solusetting* states. A variety of illustrations have been gathered to show how the material and its state governs the combination of *working pressure, temperature* and *time* allowance required to produce a particular shape.

To present the broadened view of plasticity and mass production, three chapters have been added along with new material in the appendix and through the text. Chapter XV discusses the use of semi-permanent die materials in more flexible presses for limited lot production. Chapter XVI goes into the behavior of the many types of materials in the several states of plasticity, correlating the data now available with that presented relative to metals in the earlier chapters. Chapter XVII considers the application of plastic flow methods to the molding of non-metallic as well as metallic powders and to the forming of sheet plastics and composite laminates. Illustrations of tools, equipment and methods from many industries merge into a common picture which throws much light on the planning of new products.

The author expresses an appreciation of the patience and the encouragement of Mr. H. H. Pinney and Mr. H. U. Herrick, of the E. W. Bliss Co., which made it possible to carry through this further work.

Acknowledgment of research and technical data is due the Dow Chemical Company, E. I. DuPont DeNemours & Company, Hercules Powder Company, Tennessee Eastman Corp., and many others; and to the authors and editors of the *Plastics Catalogue, Modern Plastics* and *Powder Metallurgy.* Personal acknowledgment is due Messrs. A. G. Bureau, Freeman Crampton, E. D. Eddy and Earl Cannon of the Bliss Company and G. K. Scribner of the Boonton Molding Co., for their assistance.

E. V. Crane

December, 1943

PREFACE TO THE FIRST EDITION

THE production of metallic articles in very large quantities usually involves the use of power presses. The distinctive method of press equipments is *shearing out* and *plastically working* metal to finished shape in a few quick strokes with high loads and expensive tools which are warranted only by the large quantities to be produced.

The power press itself consists essentially of a substantial frame carrying a reciprocating slide; a crankshaft and a connecting link to reciprocate the slide; a clutch and a flywheel to store and deliver energy. Variations upon this simple theme are numerous, but the principle remains practically the same.

The tools are commonly two members, a die attached to the press frame, and a punch attached to the reciprocating slide. These tools cooperate to cut, bend, pull or squeeze the metal blank into the desired shape, as the case may be.

There is endless and infinite variety in tool design. No two tool men will design even a simple die in exactly the same way. Books are available (see page 41) giving many typical examples of good practice in mechanical design. The field which they cover is interesting but too varied and too much a matter of opinion and preference to include in this discussion.

It is rather the object here to sort out the many metal-working operations into similar groups, to study their common characteristics and to establish as complete a working theory as possible for figuring operations and predicting their results. In every case the study leads back eventually to the structure and change in structure of the metal being worked. In every case the metal is stressed beyond, and usually far beyond, its elastic limit. To date, studies of the "mechanics of materials" have largely been concerned with properties of metals below their elastic limits, for structural uses. It is therefore necessary to assemble and develop theoretical data on the properties of metals in their plastic range. This study has become a large part of the present work, which, it is hoped, may aid in developing the subject further.

The author acknowledges the impetus in starting this work to the late Otto S. Beyer, an outstanding pressed-metal engineer, who described his art as "Engineering by the Grace of God."

Grateful acknowledgment is also due Mr. Joseph Klocke, Mr. William Klocke, and Mr. J. B. McCann as well as many other friends in the Bliss Company and in the trade for a great deal of data and valuable advice. The aid of Messrs T. N. Holden, W. P. Blake, A. E. Caserta and M. J. Mattera in experimental and engineering work is also very much appreciated.

The author thanks the editors of *Metal Stampings*, in which much of this material appeared, and of *Machinery*, *Western Machinery World*, the *Iron Age* and several of the engineering societies for permission to reprint from their publications.

November, 1931 E. V. CRANE.

CONTENTS

LIST OF TABLES

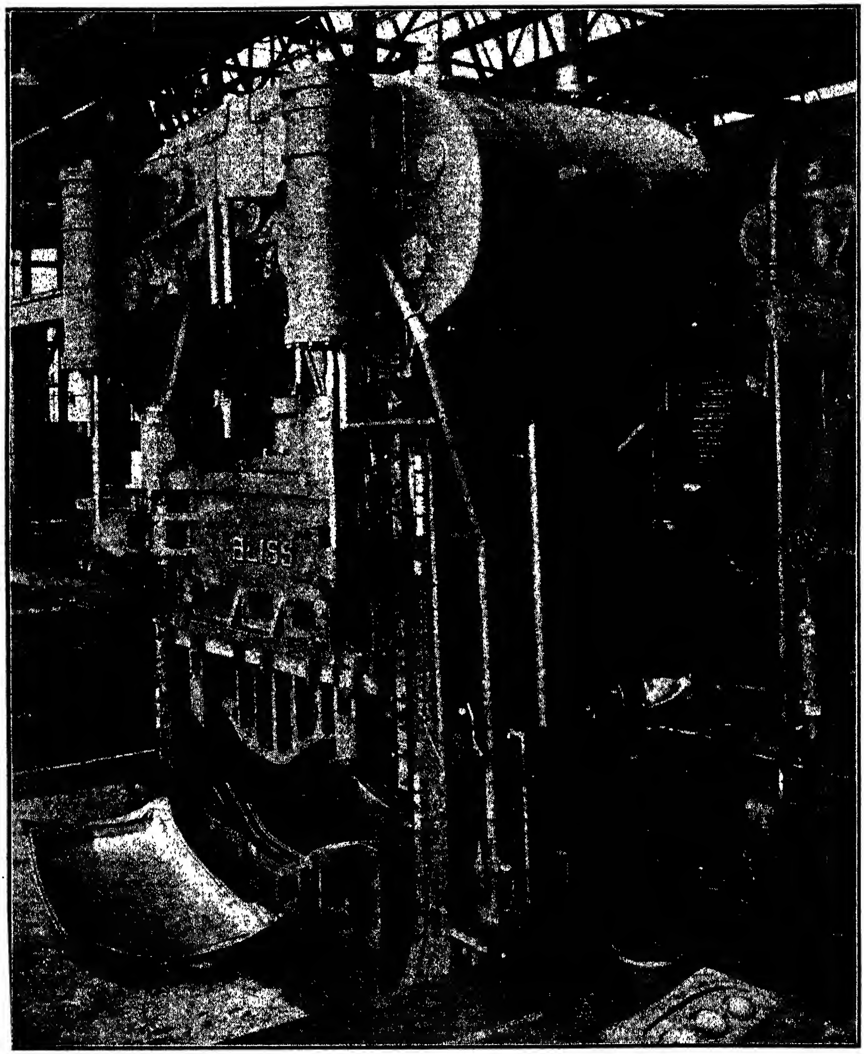


FIG. 1.—A massive press with expensive tools capable of drawing the roof of an automobile every 12 seconds at a trifling cost.

CHAPTER I

MASS PRODUCTION

THE mass-production methods of metal-working processes use carefully tooled equipment of great strength, and take advantage of the plastic properties of metals to produce an infinite variety of parts and articles at unbelievably small cost. The art of building the equipment and the art of tooling it successfully have had their principal development in a scant century. Few people realize the proportion of the erstwhile luxuries which now contribute so much to the American standard of living, which have been brought down to the level everyone can afford, by these metal-working methods.

A writer on economics once stated that "prosperity cannot be sustained unless some other industry, or combination of industries, develops as rapidly in the near future as the automobile has developed in the recent past." To him the growth of the automobile trade in fifteen years to a normal employment of three million workers was outstanding. Paralleling that growth and a vital part of it was the development, in that trade, of mass production and its methods with respect to both personnel and equipment.

These phenomenal strides in automobile making temporarily dwarfed more gradual, similar developments in other industries. The early automobiles were sawed, turned, sheared and beaten out, one at a time, without much plant equipment or any special tooling to speak of. But even in those days, kitchen utensils, watch parts, locks and other hardware, coins, tableware, collapsible tubes, pails, cans and numerous other widely used products were already well established in the use of quantity production metal-working equipment.

Here a distinction may be drawn in the machine tool trade between metal-cutting and metal-working processes. The average lathe, planer or mill may be used to produce one different piece after another with little or no tool expense; but it accomplishes its work by patiently whittling away material a little at a time. The average power press,

rolling machine or forging machine, on the other hand, requires a set of more or less expensive tools for each different piece or operation, limiting its use necessarily to fair-sized quantities. So equipped, however, it turns out the part or operation at relatively high speed and low cost.

We place a plain flat piece of sheet steel in the maw of a massive machine. There follows a hum of heavy steel gears. In the brief

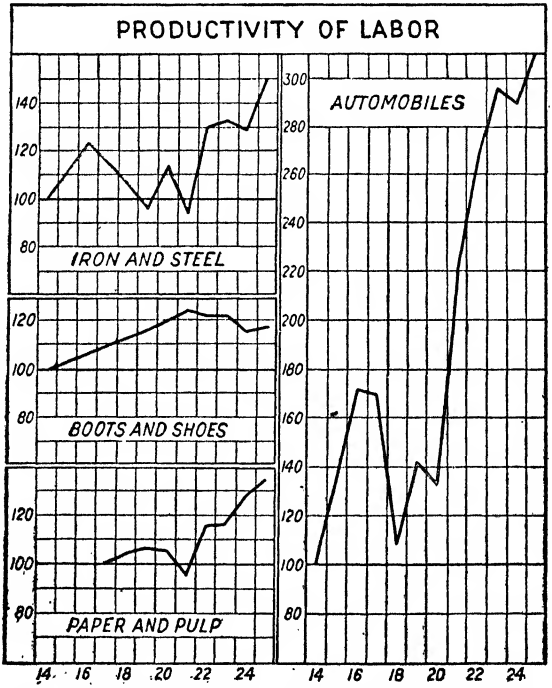


Fig. 2.—The extreme increase in production per man employed in the automobile trade, due largely to the application of press-production methods. (*Foster & Catchings*)

interval of a few seconds the cold steel bends, crowds, stretches, flows into the smooth and pleasing lines of an automobile roof (Fig. 1). The shape, if you examine it, is not a simple one. But, properly tooled, the job is done without a wrinkle, a tear or even a scratch, in spite of the change which has taken place and the quickness of the operation.

The "Productivity of Labor" chart,[1] Fig. 2, taken from data on the rise of the automobile trade, collected by Foster and Catchings, *is largely a tribute to the power press.* Wage payment systems, material-handling methods, improved arrangement of facilities, all contributed

[1] Messrs. Foster and Catchings, in the *World's Work*, Dec., 1926.

to increased output per man-hour. But their contribution amounted to little more than was reflected also in the steel, shoe and paper industries, for those methods have been heralded the country over and widely adopted. An increase to 300 per cent man-hour efficiency in ten years, however, could be accounted for only by the wholesale application of press-production methods, and that is what happened.

Ten men with suitable press equipment can, in general, produce as much as fifty men with older, small-lot methods. A curve showing the increase in use of power presses in the automobile industry would follow closely the rise of the man-hour productivity curve. Every one remembers the sudden relative drop in closed-car prices when the closed body was put on a production basis. Now we have the all-steel body, entirely press-produced. But it is not a case of the body alone. In more and more makes, nearly every metal part, except the shafting, pistons and engine block, is produced wholly or in part in presses or in related special machines.

A few illustrations may be of interest. The long side-rails and the cross-members which make up the framework of the chassis are blanked or cut out from rolled-steel sheets and then formed into shape in presses at the rate of two or three pieces per minute for each of the two operations, or faster for the smaller pieces. The rivet holes are then punched, and the rivets holding the frame together are closed in other smaller presses. Connecting rods are usually drop forgings which are trimmed in presses. Now the bosses at either end, instead of being machined to size, are squeezed between smooth-surfaced dies in six- or eight-hundred-ton coining presses at the rate of twenty or thirty per minute. The variation in the finished pieces is less than two thousandths of an inch, and this is less than the tolerance which used to be allowed in machining them. Other forgings are also press sized, and increasing numbers of both steel and brass forgings are being made in presses. In one method of making valve heads, for example, a slug is sheared from the end of a round bar; it is heated and squeezed into a ball and then into a valve and finally trimmed ready to weld on the stem. The four press operations—shearing, squeezing, resqueezing and trimming—require a total time of perhaps three seconds. Bronze wrist pin bushings made from strip material have the oil grooves stamped and are blanked out at the rate of fifty a minute. Then in another press, automatically fed, they are shaped into cylindrical form at the same speed. A final operation in a coining press insures perfect roundness, and the bushings are ready to use. Another concern produces similar bushings complete from the coil in a single press at the rate of a hundred a minute.

Small press operations, hand fed, cost only a tenth to two-tenths of a cent apiece, including all overhead charges. For very large, slow work requiring two or three men and a cumbersome machine the cost may run as high as three cents, but that is rare. Consider a closed-car body with clinched seams instead of welding; there is hardly an operation on all the metal work, between rolling the sheets and applying the paint and trimming, which is not done in presses. Certainly that accounts in a considerable measure for the low prices of modern cars.

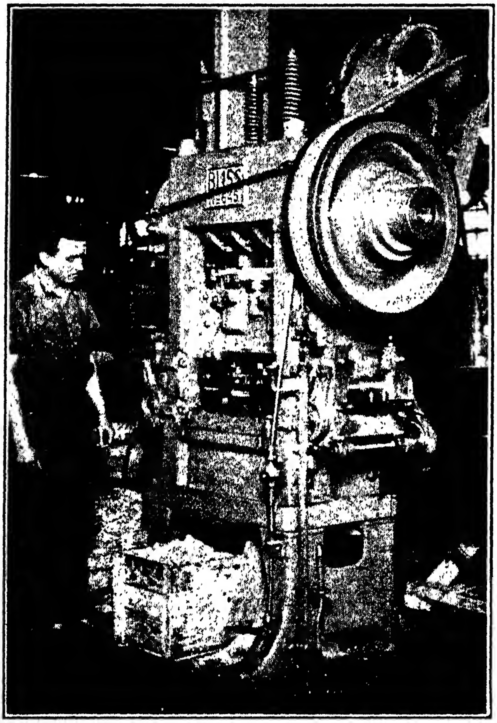


Fig. 3.—A modern development in mass production; a fully automatic high-speed unit, piercing, blanking, stamping and bending house-wiring brackets at 600 finished pieces per minute.

The secret of economy and of labor efficiency in press production is quantity. It is not worth while to make dies for a few parts, but when the quantity is a hundred thousand or a million, a thousand-dollar die costs very little per piece, although that would be rated an expensive die. And at two to fifty thousand operations per day, every day, the investment charges on a press are almost negligible. The press in Fig. 3 will complete a million operations in a day.

Even so, press and die equipment is not inexpensive, especially when it comes to changing over a whole industry from casting and machining methods to a sheet-metal-working basis. The pioneer press-production industries making watches, locks, typewriters, adding machines and the like, used small presses only, for the most part, and accumulated these gradually as they expanded, so that the initial investment did not seem so great. But the newer applications involve the production of larger parts, which naturally means large and expensive machines. A new body plant recently put in operation by one of the automobile companies required

a press equipment which, exclusive of any dies, cost considerably over a million dollars. Very often the die or tool part of an equipment costs more than the presses themselves. Possibly the above is an extreme case for a single unit, but it gives an idea of the sort of initial investment figures which must be considered in this mass-production method which continues making such strides.

Perhaps it is well to note a restraining factor. That is the fact that pressed-metal engineering is not yet nearly as exact a science as electrical engineering or steam power plant engineering. Practically every job

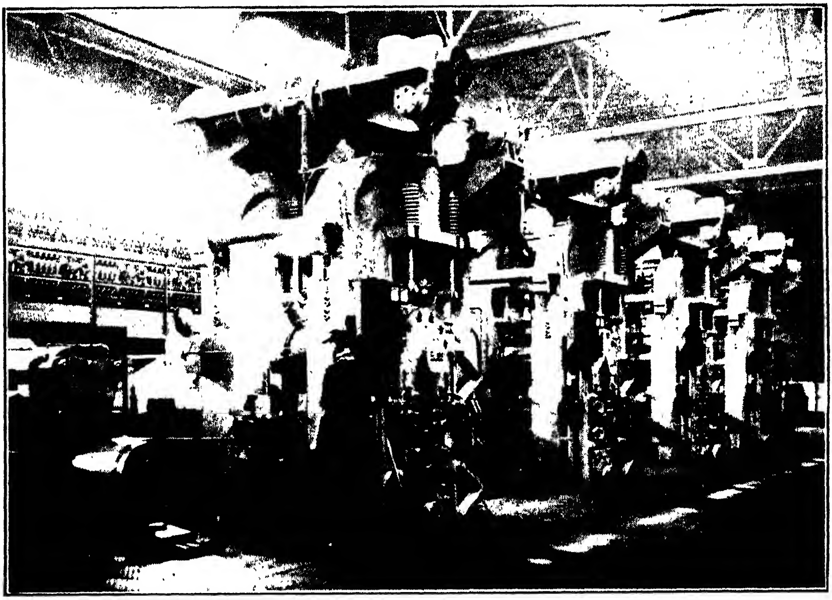


FIG. 4.—A group of "backed-up" mills for the continuous rolling of strip steel, synchronized to perform a number of reductions simultaneously.

is a problem by itself, owing largely to the number of variable factors affecting the internal condition of the metal being worked, and also to some extent to the variety in design of the tools. To a layman watching a flat piece of steel being transformed in a single operation into the shape of an automobile crankcase, the job seems simplicity and ease itself. And if he is a bit of a mechanic the tools will look very simple. Yet to lick that one job the first time cost thousands of dollars and the best efforts of expert press and rolling mill engineers.

Much of the advance which has taken place in the press trade is due to the development of rolling mills and mill practices, in the production

of more uniform and more ductile metals at reasonable prices. Fig. 4 shows an installation of roller-bearing four high or "backed up" mills for continuous rolling of strip metal. These mills are so synchronized that a single strip passing through them is undergoing a number of reductions simultaneously. Even further development will come in both rolling and annealing practice (especially of steel) to control more closely the temper of the stock and the crystal structure upon which it depends.

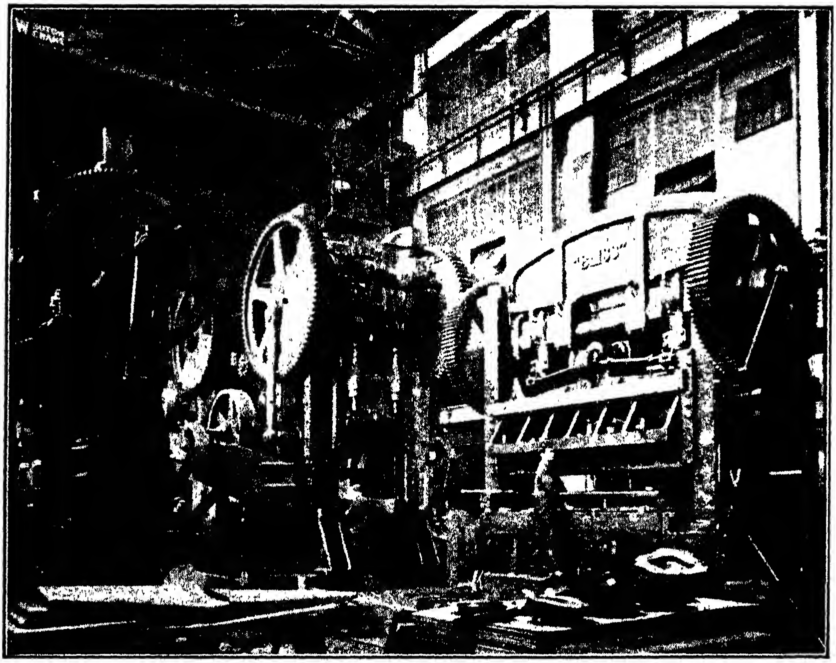


Fig. 5.—Developing tools and presses for the production of modern house-heating equipment.

It often happens that to solve a new problem or to develop a set of tools, for the best in finish or accuracy or economy in the part produced, a certain amount of experimental work is necessary. This is probably not true of any other industry, or at least not to so great an extent. It is becoming accustomed to this condition, as well as to the capital expenditure required and to the reality of the return resulting, which often restrains new ventures in this field.

Press-production methods continue to spread, however. Fig. 5 is a photograph of part of an erecting shop of the Bliss Company, taken at the time that machines for the production of new house-heating equip-

ment were approaching completion and the tools were being tried out. The press at the right, for example, takes care of several operations on the front and back panels of a heater jacket. The man in front of it gives an idea of its size, yet the steel it is forming is only $\frac{1}{32}$ in. thick. The two machines back of it form 40-in. discs of boiler plate $\frac{1}{4}$ in. thick into deep oval fire pots, and do it cold. Fig. 6 shows another press on the test floor forming a part of a sheet-metal casket. The

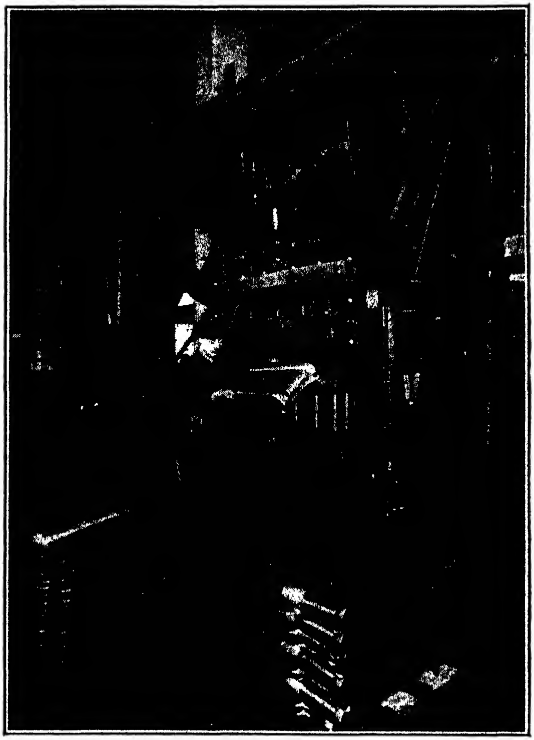


Fig. 6.—Perfecting dies on the test floor for production of part of a sheet-metal casket. The Marquette pneumatic die cushions under the press bed are of greater than usual capacity.

shape is rather difficult, but once the tool problem is solved, the cost of processing the piece is far less than the small cost of the metal required.

Modern office buildings are leaping to great heights all over the country, and with them climbs another feat of metal working, steel lath, steel edge beads, steel doors and trim, steel window frames, steel filing cabinets, steel lockers and steel furniture—all products of rolling machines, brakes and presses.

Adding machines, comptometers and bookkeeping machines, all comparatively recent developments, are an outgrowth, so far as press-production methods are concerned, of the typewriter industry. The radio industry also, though requiring great numbers of presses, presents comparatively few new tool problems. Elsewhere in the electrical industry, manufacturers of washing machines, mangles, vacuum cleaners, automatic refrigerators, cooking appliances and lighting fixtures continue to add to their press equipments. And the story is always one of increased production and increased man-hour efficiency.

Rearrangement to a final shape in mass production now applies to many organic plastics and some ceramics, but as the theories developed in the working of the old and new metals points the way for other materials, the metals are considered first.

CHAPTER II

ESSENTIAL METALLURGY

ANY discussion of the press-working methods must deal with a great variety of " operations," that is, of specific ways in which material is transformed from one shape to another. Plastic material may be *cut*, or *bent*, or *pulled* or *pushed* step by step into its final condition. Into one of these four groups, or a combination of them, most press operations fall fairly clearly.

Empirical methods and experience have sufficed for years in the judging of press capacities and the capabilities of dies with the result that the trade has not progressed from an engineering standpoint, to compare, for example, with the electrical, power and civil engineering groups. Sound engineering theory must be built up rather slowly on account of the number of variable factors entering into most operations. These variables must be isolated, run down separately and then brought together systematically.

A great many of the causes for behavior and for differences in behavior in the material being worked in the tools and the presses lie within the structure, in its reaction to different stresses and treatments. To exceed the elastic limit of one piece of steel and shape it plastically without exceeding its ultimate strength, and breaking it; or to stress another piece of steel to the breaking point without damaging the steels which are being used to perform that operation repeatedly, is a problem in structure and treatment. To discover the stresses occurring, which limit how far we may go, requires careful figuring. These foundations in metallurgy and mechanics are obvious. A few definitions must be endured, however, to get a starting point.

Mechanics of Metals.—Certain " mechanical properties " of metals define their behavior under internal forces or " stresses," due in turn to external forces. The terms tensile, compressive and shearing stresses indicate the direction of the forces, whether pulling, pushing or transverse slicing, respectively.

Metals may be deformed elastically in compression or tension within certain limits, returning to their original shape when the deforming force is removed. The amount of the elastic stretch, deflection or change

is small, but may be of interest in both presses and tools, owing to resultant inaccuracies or to insufficiently rigid support. The elastic limit of a metal measures the greatest stress per unit of area under which it will behave elastically. This limit is materially lower under frequently repeated stresses or fatigue conditions, as in a press frame or crankshaft, than it is under occasional loading.

When metals are loaded beyond their elastic limit they retain a permanent set or change of form. As the loading continues, the metal is deformed plastically more and more, until fractures start. A complete break follows quickly, at what is known as the ultimate strength. Shearing and punching operations stress the metal being worked, beyond its ultimate strength. Other press operations, such as bending and drawing, etc., utilize the range between the elastic limit, which must be exceeded, and the ultimate strength, which must not be exceeded.

Ductility and malleability are qualitative terms describing the relative ability of metals to stand plastic deformation without fracturing. Malleability refers particularly to deformation under pressure, as in rolling, swaging, forging, etc. Ductility refers rather to tensile working as in drawing, and is measured in a general way by the elongation of a test piece and the reduction of its cross-section when pulled in a testing machine. Ductility and malleability are not necessarily the same for the same metal (Table XI), and vary considerably with changes in temperature.

Hardness and the hardening of metals are of especial interest in press work. The hardness of a material is variously indicated by its resistance to cutting, to abrasion and to indentation, and by its resilience. The last two are made the basis of the Brinell and Shore Scleroscope hardness tests, respectively.

Increasing hardness, or resistance to deformation, seems to follow fairly closely and logically with increases in strength as indicated by the tensile test. The Brinell indentation test based on permanent deformation is more in line with the ultimate strength; the Shore rebound test is better indicative of elastic limit.

Increasing hardness and increasing strength or resistance are the result of structural change within the metal. This change may be accomplished by the brute force of cold working as in rolling, swaging or drawing. It may also be accomplished by gradual heating, and then arresting the changed structure by means of sudden cooling, as in the heat treatment of dies. Alloying of the pure metals may contribute to increased hardness, either in the normal state, under cold working, or by heat treatment. Fig. 7 for copper is illustrative of the hardening of

metals, with increased resistance and a proportionate reduction of ductility, by plastic deformation or cold working. It also indicates, to the right, the return of the structure and properties to their original condition during annealing.

The explanations of these common mechanical properties of metals and of the changes in properties to be developed are found in metallurgy.

Structure of Metals.—It seems now to be well established that every element, be it iron, mercury, sulphur, hydrogen or another, may be theoretically subdivided to a final point where it consists of a minute, positively charged nucleus surrounded by a group of rapidly moving, infinitely small particles, each carrying a unit negative charge of electricity, known as electrons. The group is the atom, and that which distinguishes every atom of one element from every atom of another element is its number of electrons. If the elements are arranged in order according to their atomic weights and are numbered in that order from 1 to 92, with a few omissions, these numbers, known as the atomic numbers, indicate the number of electrons per atom in each element. Thus hydrogen has 1 electron per atom, helium has 2 and iron has 26.

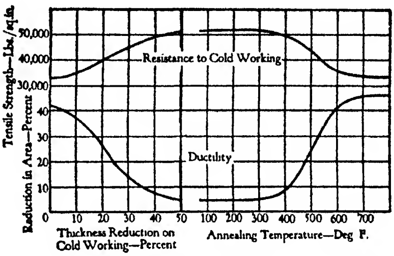


FIG. 7.—Cold working reduces the plasticity and increases the resistance to further working, the original state being restored by annealing. Material: copper. Crystal pattern; face-centered cubic.

Aluminum,[1] atomic number 13, has 13 negative electrons about a highly concentrated nucleus, which in turn is said to contain 27 positive electrons or protons and 14 negative electrons, giving a positive charge of 13. The 13 external or planetary electrons are probably arranged in three groups: inner shell 2, next group 8 and outer group 3. This outer group, called the valence group, is active in forming chemical combinations and determining the valence or combining power of the atom. The three groups are referred to as three quantum levels of 2, 8 and 3 electrons, according to the developing quantum theories which seek to account for the various properties and characteristics of atoms. The radius of the sphere of "atomic domain," the approximate size of the atom group, is given geometrically as 0.000,000,005,6 in.

Electrons in any atom are in constant motion relative to their nucleus with tremendous velocity and are held in constant relation to it

[1] Edwards, Frary and Jeffries, "The Aluminum Industry," Vol. II, Chapter II, McGraw-Hill Book Co., New York, 1930.

by strong attractive forces. The volume dominated by the atom has a diameter of the order of 50,000 times the diameter of the electrons.

The assembled atoms of any element exert upon each other strong attractive and repulsive forces, illustrated roughly by tensile and compressive strengths in metals and surface tension in liquids. These interatomic forces are modified by the application of heat. At all temperatures above absolute zero, the atoms of the solid elements are in a state of vibratory motion about their nuclei. The frequency of vibration is of the order of 6,000,000,000,000 cycles per second and does not vary greatly with the temperature. The amplitude or amount of vibration does increase with the temperature, however, thereby increasing the kinetic energy of the particles.

The elements may exist in gaseous, liquid or solid state according to their temperature. In the gaseous state the atoms, or the molecules into which they combine, are so violently agitated that the forces of attraction between them are insufficient to cause even temporary combinations. As the gas cools, the kinetic energy is reduced until it can be overcome by the forces of attraction sufficiently to cause condensation into the more compact liquid state. Here the frequent collisions cause temporary combinations of molecules only to be broken up again by further collisions. This constant shifting of the bonds between molecules is offered in explanation of the fluidity of liquids.

Continued cooling further reduces the kinetic energy of the moving particles until it is entirely overcome by the attractive forces and solidification takes place. In solidifying there is a natural tendency, due to the forces between them, for the molecules to assemble themselves in the definite relation or pattern which characterizes the crystal of the element, solution or compound. When solidified the atoms remain in motion about their equilibrium positions. This motion becomes less as the cooling continues, accompanied by shrinkage of the metal and proportionate moving closer together of the atoms.

In solidifying, crystals start to form from many points at the same time. Any one crystal grows gradually from a nucleus, the atoms arranging themselves in proper pattern because of the forces between them until the boundaries interfere with the boundaries of other crystals developing all around. Under common conditions, each crystal of any one material is identical in pattern and spacing with any other, but the pattern has definite directional qualities, and it is uncommon that any two adjacent crystals are oriented in just the same manner. Accordingly a section of a metal when polished, etched and magnified, as in Fig. 8, shows many irregular crystals or grains, with some material at the boundaries not oriented with either adjacent crystal.

The common space lattices or patterns of metallic crystals, as explored by x-ray analysis by a number of investigators, are fairly simple geometrically. The metals are monatomic, that is, have one atom per molecule. The atoms arrange themselves in space in several patterns such that each atom is located similarly to every other one, by reason of the forces between them.

FIG. 8.—Irregular boundaries of (white) ferrite crystals and (black) pearlite in forged 0.30 C steel. ×70. (*Holden*)

Thus one pattern known as the face-centered cubic space lattice is illustrated at the left in Fig. 9. Gold, silver, lead, nickel, gamma iron, copper and others crystallize in patterns built up of this lattice. As illustrated at the right in Fig. 9, it is possible to indicate a number of planes through different groups of points. A *series* of planes parallel to *any one* of these planes of symmetry will take in *all* atoms in the crystal and will be equally spaced. Between these planes are areas of weakness.

When metal is strained within its elastic limit the atoms are forced closer together or farther apart but return elastically to their normal positions as the strain is released. When metals are permanently deformed by cold-working, they are stressed beyond their elastic limits, beyond what the bonds between atoms will stand, and a slippage or rearrangement occurs along some of the planes of weakness which happen to be in the proper angular relation relative to the straining force.

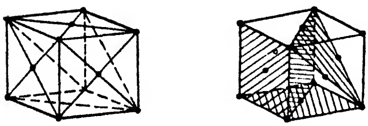


FIG. 9.—Relative arrangement of atoms and some typical planes of symmetry in the face-centered cubic lattice, the pattern in which most ductile metals crystallize.

These have become known as slip planes, and metal which has been cold-worked shows slip bands through the crystals, quite clearly in some cases. Fig. 10 [2] shows such slip bands in twinned crystals of alpha brass. As deformation progresses in a single crystal, slippage starts along some plane of weakness, and proceeds until the resistance to slippage increases so that further movement must occur on another plane.

After severe cold-working the metals which do not anneal at working temperatures show considerable increase in hardness and also in resis-

[2] Jeffries and Archer, "The Science of Metals," McGraw-Hill Book Co., New York, 1924.

tance to further working, Fig. 7. Their crystalline structure shows material distortion, and a good deal of internal strain remains along partially displaced slip planes between atoms. As heat is gradually applied, increasing the kinetic energy and corrective capacity of the electrons and atoms, the distorted and strained large grains break up or recrystallize into many small grains in equilibrium. As heating continues, the smaller crystals gradually dissipate, their atoms lining up in the patterns of adjacent larger crystals. As this grain growth proceeds, the metal becomes softer and more workable, returning, when completely annealed, to a normal state, Fig. 7. The curve reproduced in Fig. 11 shows approximately the relation between average grain size

FIG. 10. — Crystals of worked alpha brass showing slip bands. ×85. (*Mathewson*)

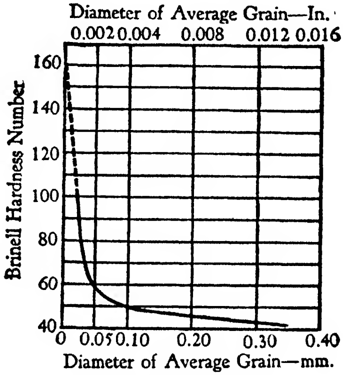


FIG. 11.—Relation between grain size and Brinell hardness in alpha brass. (*Bassett and Davis*)

and hardness found by Bassett and Davis in their studies of cartridge brass.

Many press operations do not deal with pure metals. In fact, most press working is concerned principally with steel, which is typical of aggregates of elements, compounds and mixtures of the two; and brass, which is typically a solid solution in its common phases.

Two metals may be soluble in each other in any proportions, as copper and nickel, which both crystallize in the face-centered cubic pattern with about the same lattice dimensions. It is interesting to note that, when two metals form a continuous series of solid solutions, the hardness and strength of the solutions are increased beyond those of either metal. This is shown in the hardness curve for silver and gold in varying proportions, Fig. 12. The increase is attributed to increased resistance to movement along the slip planes, due to a distortion of the crystal lattice.

Copper and zinc do not crystallize in similar patterns and do not form a continuous series of solid solutions. The alpha brass series up to about 36 per cent zinc, when properly homogeneous, shows a single crystalline pattern, the face-centered cubic lattice typical of copper. It is believed that the zinc atoms occupy the positions of some copper atoms in the lattice. Alpha brass is ductile and suitable for cold working, an attribute characteristic of the face-centered cubic space lattice. The beta brass series, of about 45 to 48 per cent zinc, crystallizes with the body-centered cubic lattice, differing therein from both copper and zinc. It is harder and less ductile than the alpha series but better adapted for hot working. The gamma phase may be recognized as a

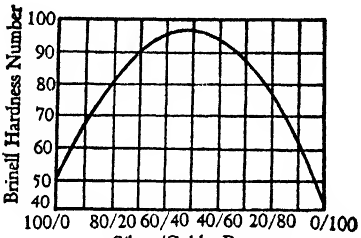


FIG. 12.—Variation in alloy hardness according to proportions of gold and silver, in solid solution. (*Jeffries and Archer*)

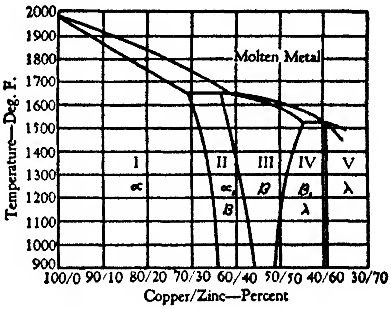


FIG. 13.—Constitution diagram of copper-zinc alloys, alpha brass in areas I and II, beta brass in areas II, III and IV and gamma brass in areas IV and V. (*After Jeffries and Archer*)

compound of the formula Cu_2Zn_3 and is quite hard and brittle, spoiling the mechanical working properties of alloys in which it occurs. A portion of the copper-zinc equilibrium diagram showing the variation of phase with temperature and composition is shown in Fig. 13. Solid solution alloys, when worked into a homogeneous state, behave like pure metals in the growth of grains.

The most interesting portion of the steel group to the pressed-metal worker is the beginning of the iron-carbon diagram. This applies particularly to drawing and forming operations where plasticity is essential under a considerable amount of cold working.

At ordinary room temperatures carbon steel is an aggregate or mixture of ferrite and pearlite up to 0.85 C (0.85 per cent carbon) and of pearlite and cementite above that to about 7.0 C. Ferrite is pure iron and is plastic. Cementite is iron carbide, Fe_3C, and is hard, brittle, quite the opposite of plastic. Pearlite is a mixture of plastic

ferrite and hard cementite, in the proportions of about 13 per cent cementite and 87 per cent ferrite. The ferrite in the mixture, being plastic, will yield and permit the cementite to be broken up into fragments under cold working. Whether in plate or fragment form, however, the cementite makes the pearlite mixture materially harder and stronger than the pure ferrite, owing to its interference with movement along the slip planes. The proportion of pearlite varies from practically zero at 0.05 C to 100 per cent at 0.85 C, the balance, up to that point, being plastic ferrite. The lower the carbon content and the proportion of pearlite, the better is the plasticity of the steel for cold working. Above 0.85 C free cementite begins to appear, forming a more and more rigid network of hard, brittle and unworkable material about the pearlite. The chart, Fig. 19, shows the relative variations in the properties of the plastic ferrite-pearlite phase. Ferrite, being the continuous constituent and a pure metal, is susceptible to annealing for recrystallization and grain growth after cold working.

The hardening of the higher-carbon steels and alloy steels for dies and tools is subject to too many variations and gaps to be reviewed. Structurally the hardness of such steels is attributed, by Jeffries and Archer, to interference with ease of movement along the planes of weakness. This is obtained by reducing the crystals to small size, so that there are many boundary interferences, and by causing the precipitation of finely divided hard cementite particles through the crystals, so that these also serve to retard slippage. Initial distortions never occur in plastic materials by direct tearing apart or overcoming the full interatomic attraction or cohesiveness. There is always a gradual movement at an angle to the deforming force, taking advantage of the orderly and comparatively extended lanes between rows of atoms. Maximum reduction of the ease of sidewise displacement along these lanes is the object in hardening.

So brief a discussion of metallurgy is necessarily limited to touching on general principles only. The next step, however, is to obtain an orderly arrangement of press operations for purposes of discussion.

Grouping Press Operations.—It was suggested at the beginning of this chapter that most operations could be grouped according to whether the metal were cut, bent, pulled or pushed into shape.

The first, the shearing group of operations, will include blanking, punching, compound blanking and punching, follow die punching and blanking, blanking and repunching, perforating, shearing (on one or two sides only of a shape), shaving, broaching, trimming and hot punching. All these are essentially similar in intensity and in that they stress the metal in shear to the point of fracture, i.e., beyond its ultimate

strength. All the other groups work the metal plastically above the elastic limit, but below the (true) ultimate to avoid fractures.

The second, the forming group of operations, includes, principally, various methods of bending plus operations known as curling, burring, necking, expanding, beading and bulging, which seem to fit better here than elsewhere. The bending operations involve stressing the metal in tension on one side of its neutral axis and in compression on the other side in general according to the beam formulas plus an allowance for short spans. Some of the other operations include also stretching the metal but not in such a manner as to place them under the drawing classification.

The third, the drawing group, includes the operations in which metal is caused to flow plastically from one shape to another, under primarily a pulling or tensile loading. Very high compressive stresses result, in the area in which the shape is being changed. These help to produce the large unit deformations required but bring in other troubles, including wrinkling, cracking, etc. All drawing operations stress the metal beyond its elastic limit but within its ultimate strength, and perform, in most cases, a very large amount of cold working so that the importance of a wide plastic range and a proper initial crystalline structure is apparent.

The fourth, the squeezing group of press operations, primarily involves a compressive stress in the metal but may result in tensile strains in some instances. This, the severest of all press work, is subdivided into four groups according to potential severity. These are headed: sizing, swaging (or cold forging), coining (including embossing and some stamping), and extrusion. Potential severity refers to the fact that typical operations of each group, performed on similar material in similarly rigid presses, would involve progressively higher unit pressures on the tools in each case. As a matter of fact, we work practically to the limit of what the tools will stand in each case. Thus the ultimate working capacity of high-grade steels carefully hardened is approached about equally in the extrusion of zinc, the coining of brass, the swaging of soft steel and the sizing of a moderately hard worked steel. A fifth group of operations, forging (hot), is included with those mentioned above on account of its mechanical similarity to the swaging group.

The Plastic Working Range.—Before proceeding to a discussion of the several groups of metal-working operations it seems advisable to consider a little more specifically the terms and implications of plastic working with which they are all concerned. Physical properties of metals below their elastic limits have been thoroughly explored and are of wide-spread interest for purposes of structural design. They also

apply to the structural design of the stampings which are produced in power presses, but that is beyond the scope of the present work.

In producing the stamping we work entirely beyond the elastic limit, or better, beyond the yield point of the metal. Fig. 14 [3] shows the results of the conventional tensile test of a series of annealed carbon steels. The metal behaves elastically up to a higher and higher stress before it begins to yield, as the carbon content is increased. At the same time the amount that it elongates, or moves plastically, becomes less and less. It may be noted here that the common "ultimate tensile

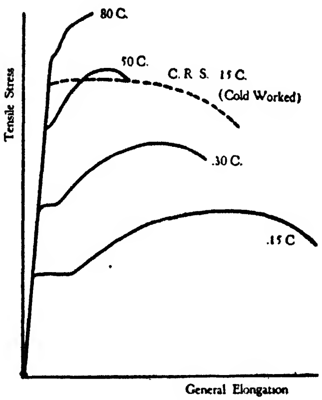


FIG. 14.—The tensile test shows graphically differences in yield point and plastic range due to carbon content, for annealed steels. (*Professor G. E. Troxell*)

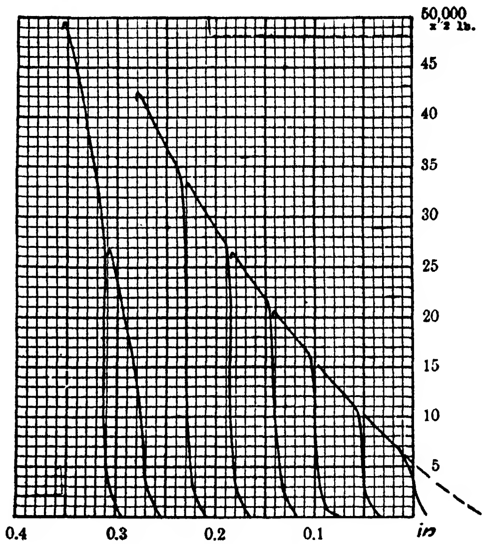


FIG. 15.—Compression test curves for Tobin bronze as recorded, showing progressively increasing yield points as the metal is cold worked from annealed states. (*E. W. Bliss Company*)

strength" is merely the highest stress recorded (the highest point on the curve) divided by the cross-section area of the specimen before the test started. This area has reduced considerably before the maximum stress is reached and reduces more rapidly than the stress thereafter. It is therefore neither an "ultimate" nor a unit stress, and can be of relatively little value in gauging plastic working operations.

It will be noted also that a 0.15 C steel which has been cold rolled (dotted curve) shows a very much higher yield point than the annealed

[3] Professor G. E. Troxell, "The Physical and Mechanical Properties of Steels," *Western Machinery World*, San Francisco, April and May, 1928.

specimen. This illustrates how the metal has been strain-hardened by the slip plane movement involved in cold-working it. It also shows that considerably more distortion (elongation in this case) is possible before the available slip planes have been used up, when the fracture occurs.

Another illustration of progressive strain-hardening in plastic working is offered in Fig. 15. Here a cylindrical slug of annealed Tobin Bronze was compressed step by step in a recording Olsen testing machine. It was squeezed down about 0.050 in., removed, measured, tested for hardness, returned to the machine, squeezed another 0.050 in., removed again, etc. Each time the metal was returned to the machine it behaved elastically up to a new and higher stress which was determined by the amount it had been cold-worked before. From each new yield point the metal moved plastically again, the stress rising as a continuation of the previous plastic working curve.

After about a 50 per cent compression, the slug was reannealed. The recrystallization restored to the strain-hardened metal a new unstrained crystal structure. Therefore the new compression curve began again at a low yield point. It rose more rapidly than in the first case, however, as the slug had now become much thinner and larger in area.

Compressive and Tensile Movement.—If a metal is cold-worked in tension (pulling), or in compression (squeezing), the absolute stresses per unit of area and the strain-hardening should be the same for the same amount of movement of the same metal. Owing to the miscellaneous orientation of crystals, the resistance to movement is the same in any direction through annealed or uniformly worked metal. To be sure, we meet a rising stress in compressive tests and a falling stress in tensile tests, but that is clearly due to increasing or decreasing cross-section areas in stress.

Fig. 16 is borrowed from discussions of single crystal deformation,[4] to show diagrammatically the mechanism of reduction of area in tensile deformation, and increasing area in compression loading. It is again a case of plastic deformation; of minute movements occurring along many slip planes in many different crystals. Those slip planes which happen to be oriented at about 45° to the direction of the outside forces are the most favorably placed, movement along such planes stopping as it meets sufficient obstruction, and continuing elsewhere, where the resistance is not so great. Minute slippages and boundary interferences must

[4] Sykes, W. P., "Effect of Temperature, Deformation, Grain Size and Rate of Loading on the Mechanical Properties of Metals," Trans. Am. Inst. Mining Eng., Vol. 60, p. 780.

be imagined, but the illustration should serve, with its simple and exaggerated movements, to show how the area changes with the direction of loading. Thus the left-hand sketch shows an unstrained piece. The next two show the first movements if it is stressed beyond its yield point in tension. The next two show the first movements if it is stressed in compression.

To relate such movements in comparable values, volume is taken as the criterion, as it has been shown (by Houdremont and Burklin) that the actual change of volume of metal under severe stress is negligibly small, say below 1 per cent under conditions which might be anticipated in punch press operations.

Thus in Fig. 17 are shown side and end views of two rectangular pieces which have identically the same volume. The darker or longer

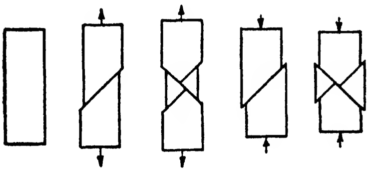


FIG. 16.—The beginnings of slip-plane movement under tension and compression are shown diagrammatically to illustrate the attendant cross-sectional contraction and expansion.

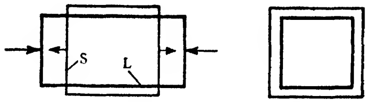


FIG. 17.—As the volume remains constant, the same amount of work and the same *unit* stresses occur in either tensile or compressive changes from one shape to the other (for practical purposes).

one will be indicated by a subscript L applied to its dimensions in formulae. The lighter or shorter piece will be indicated by a subscript S.

If the longer piece is squeezed sufficiently by external forces in the direction of the dark arrows, it may be compressed (approximately) to the shape and dimensions of the light piece. Conversely, if the light piece is stretched in tension in the direction of the light arrows, it may be elongated to the shape and size of the dark piece. Shapes are somewhat distorted by external influences in actual tests, but that does not bear upon the analysis.

As the internal forces which hold the atoms of the metal in uniform relation to each other will offer the same resistance to slip plane movement in any direction (in uniform material), the force *per unit of area* will be the same to start movement in either direction, that is, from long to short (compression), or from short to long (tension).

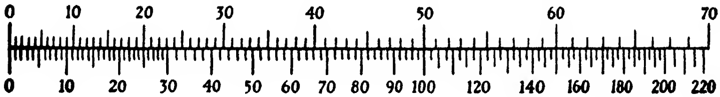
As the volume is constant and the limiting shapes are just reversed, the internal working of the metal will be the same from one position to the other, whether the change is in tension or compression. Therefore

the strain hardening will be the same and the final stress (or force) *per unit of area* will be the same regardless of direction.

To be sure, the total force or resistance is generally increasing in the compression test (regardless of strain-hardening) because the area of the cross-section increases as the test progresses. Conversely, the total force or resistance is generally decreasing in plastic elongation as the section area is progressively decreasing.

The work done or distance moved or change in either case is ordinarily expressed as a percentage of the *original* dimension. Thus a 10 per cent elongation is not the same as a 10 per cent compression. Referring again to Fig. 17, if the length of one piece is 1.0 in. and of the other 1.1 in., then the per cent elongation is $\frac{1.1 - 1.0}{1.0} = \frac{0.1}{1.0}$ or 10 per cent; and the per cent compression is $\frac{1.1 - 1.0}{1.1} = \frac{.1}{1.1}$ or 9.09 per cent.

Read Upper Scale, $(A_L - A_S) \div A_L$
Per Cent. Reduction in Area; wire drawing or tensile test
Per Cent. Reduction in Shell Diameter; shell drawing, necking
Per Cent. Reduction in Thickness; coining, swaging



Read Lower Scale, $(L_L - L_S) \div L_S$
Per Cent. Elongation; tensile test, wire drawing
Per Cent. Expansion in Shell Diameter; bulging, burring

FIG. 18.—Scale of equivalent distortion effects (compressive and tensile).

Fig. 18 shows a scale for the easy comparison of increasing or decreasing percentage changes. Of course the directional difference becomes more apparent with increasing magnitude, as that a 100 per cent elongation (1 in. to 2 in.) is the reverse equivalent of a 50 per cent compression (2 in. to 1 in).

An interesting comparison, bringing out a failing in the tensile test as an indication of capacity for plastic working, is reported per cent elongation in 2 in. *vs.* per cent reduction in area (at the neck). Referring again to Fig. 17, if A represents cross-section area (at the right) and L represents length, the expression for per cent reduction in area is $\frac{A_L - A_S}{A_L}$, which suits the upper scale of Fig. 18. The expression for per cent elongation is $\frac{L_L - L_S}{L_S}$, which satisfies the lower scale. Accordingly, the two may be compared directly.

Plastic Range Physical Properties.—The ordinary "ultimate tensile strength" and per cent elongation in 2 in. do not represent at all the maximum stresses or movements met in plastic deformation. In Fig. 19, however, these and other tensile test values for steels have been translated into more useful limits for cold-working. Similar conversions have been made in Table I for Tobin Bronze.

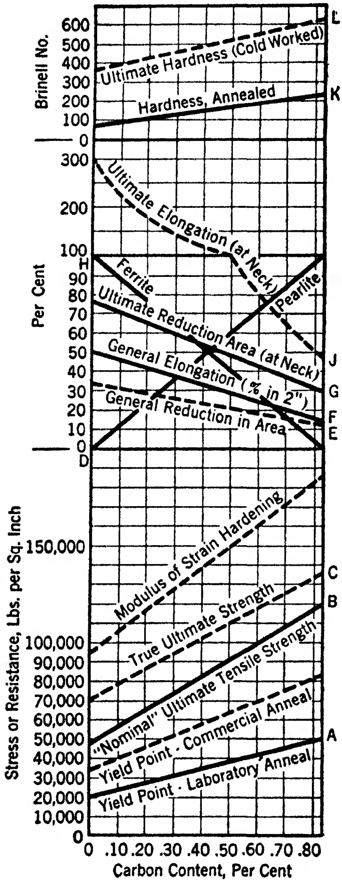


FIG. 19.—Physical properties of the ferrite-pearlite range of steels, showing the plastic range properties (working at room temperatures). Test data from Jeffries and Archer. Dotted curves derived or approximated from other curves and Figs. 14 and 18.

In Fig. 19, the low and high limits of curves *A*, *B*, *F*, *G* and *K* were taken from data [5] by Moore for Armco Iron and by Jeffries and Archer for substantially pure pearlite. These limits and the fact that they are connected by approximately straight lines are confirmed by Professors Sauveur and Troxell.

Curve *C*, Fig. 19, showing the actual unit stress reached at the neck before the tensile specimen breaks, is approximated from the curve end stress values in Fig. 14 and proper change of area values at the neck from curve *G*. In Table I, both the nominal and the actual tensile strengths were taken from tests of standard tensile specimens, Fig. 20. The actual stress at the neck, in this case, is around double the nominal "ultimate tensile," and is practically the same whether performed on the annealed or cold-worked sample. If no surface scratches or flaws appear to cause premature failure, the fracture might properly occur when the metal is completely strain-hardened, that is, when all suitably placed slip planes have been used up. This should take place at about the same final unit stress, whether the working was started with complete annealing or not. In straight compression about the same limiting unit stress may be expected, except that fractures may not spread into obvious failures quite as quickly.

[5] Jeffries and Archer, "The Science of Metals," first edition, pp. 152 and 374, McGraw-Hill Book Co., New York, 1924.

The relative identity of tensile and compressive unit stresses or yield points at four stages in the strain hardening of the metal is also shown in Table I. This is in confirmation of the discussion in connection with Fig 17. The strain hardness ratings given, of 0, 12, 20 and 29 per cent for the four stages, are tentative, and the method of arriving at them will be discussed in a later chapter (VII). The slightly higher compressive unit stress in each of the higher stages is attributed to a pyramiding of pressure in the relatively low slugs used.

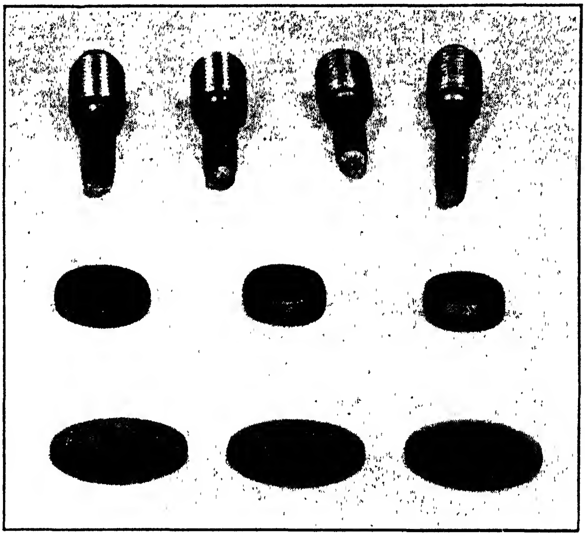


Fig. 20.—Typical Tobin bronze specimens after tensile, compression and shear tests. See Table I.

The usual "per cent reduction in area" is a true ultimate value and may be taken as an approximate plastic limit. From it we may read the equivalent "ultimate elongation" at the neck by means of the scale in Fig. 18. The result is shown in Table I in comparison with the "general" (or average) elongation in 2 in. Similarly in Fig. 19, curve J showing ultimate elongation was plotted, by means of Fig. 18, from curve G, reduction in area. Elongations of 100 to 300 per cent seem excessive at first but are actually obtained in plastic working operations. With the generation or application of a little heat to lower the strain hardening rate, such limits have been materially exceeded especially in wire drawing.

Table I

PLASTIC PHYSICAL PROPERTIES OF TOBIN BRONZE

Analysis (Published): copper, 61.2 per cent; zinc, 37.3; tin, 0.9; lead, 0.4; iron, 0.2.

Physical Test	Annealed 1100° F. ½ Hr.	As Received
(Ultimate) Reduction in area, per cent	53	48.5
(General) Elongation in 2 in., per cent	46	31
(Ultimate) Elongation (at neck), per cent	113	94
(Nominal) "Ultimate tensile," lb. per sq. in.	60,500	66,000
Actual ultimate tensile, lb. per sq. in.	120,000	118,000
(Nominal) Resistance to shearing, lb. per sq. in.	36,400	42,400
(Initial) Yield point:		
At approximate strain hardness of, per cent	0	12
Tensile test, lb. per sq. in.	25,000	52,000
Compression test, lb. per sq. in.	24,500	59,000[a]
After 20 per cent reduction = 25 per cent elongation:		
At approximate strain hardness of, per cent	20	29
Tensile test, lb. per sq. in.	71,000	83,000
Compression test, lb. per sq. in.	80,000[a]	92,300[a]

[a] Higher than equivalent tensile yield points on account of pyramiding effect in compressing low blanks.

The absolute strain hardness ratings are tentative.

The cold working for the second group of yield points was performed at about 70° F.

CHAPTER III

SHEARING METAL IN DIES

BLANKING, punching, trimming, shaving and otherwise cutting metal to shape in dies, forms a distinct group of press operations the subdivisions of which have much in common. It is the largest of such groups, and in general the simplest, although it still offers a number of unsolved problems and not a few complications.

Mechanism of Shearing.—Shearing resembles testing in tension very closely. An increasing load stresses the metal in shear (or in tension) up to its elastic limit accompanied by the small proportional deflection of elastic material. As the load increases beyond the elastic limit, plastic deformation occurs through slippage along interatomic planes of the crystals in the area under stress. This proceeds according to the material, and is accompanied by a reduction of the area under greatest stress until the ultimate strength of the material is exceeded. The surface crystals of the metal being cut (Fig. 21 *B*) are more severely stressed than those in the interior as they are being forced to conform plastically to the profiles of the punch and die. The sharp cutting edge serves to localize the highest stress along one line in the surface material. Consequently when the strains in the material moving over the cutting edge reach sufficient intensity, fractures start there and spread through properly oriented cleavage planes of adjacent crystals in the zone of stress and in the general direction of similar fractures starting from the opposite cutting edge. Thus both in shearing and in the tensile test the metal is stressed beyond its elastic limit, reduced in cross-section area (plastically), and fails with a tensile fracture through the reduced area.

The typical tool for punching, blanking, etc., is a symmetrical affair cutting all the way around the desired shape and therefore setting up balanced strains in the material during cutting. Exceptions to this are found in line shearing, shearing on two sides of a rectangle, notching three sides of a rectangle, cutting half blanks and similar unbalanced operations which will be discussed in order.

The typical tool consists of a punch and a die, each in suitable holders. The punch is ordinarily the moving member and usually enters the die. Fig. 21 is arranged to show diagrammatically various

phases of the shearing operation in such a typical tool. The illustration shows the metal as if in strata form to indicate the manner of deformation.

The sketches *A*, *B* and *C* in Fig. 21 show the progress of the punch through the metal under theoretical conditions of cutting annealed and plastic mild steel in a die having suitable clearance. In the first position, deformation is just beginning to take place. In the second (*B*), it has proceeded to a point where the ultimate strength of the surface material has been exceeded at the cutting edges and fractures have started. In the third (*C*), with very little additional progress of the punch, these fractures are spreading rapidly toward each other to meet in a clean

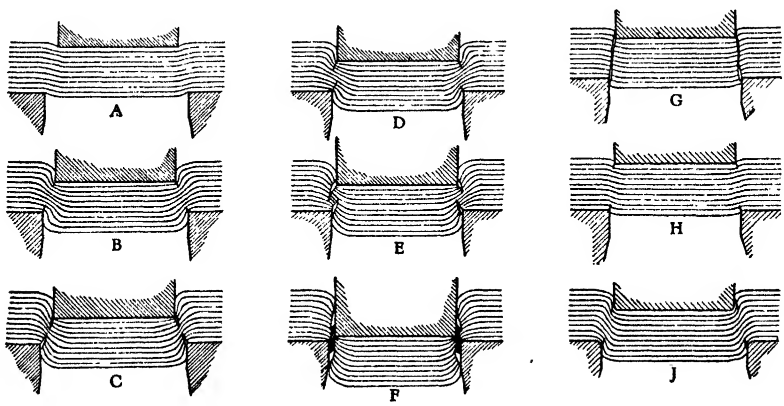


FIG. 21.—Progress of a punch through sheet metal showing plastic deformation and fracture: *A*, *B*, *C*, ductile metal with ample clearance; *D*, *E*, *F*, similar metal with insufficient clearance; *G*, *H*, hard metal with sufficient clearance; *J*, effect of dull cutting edges.

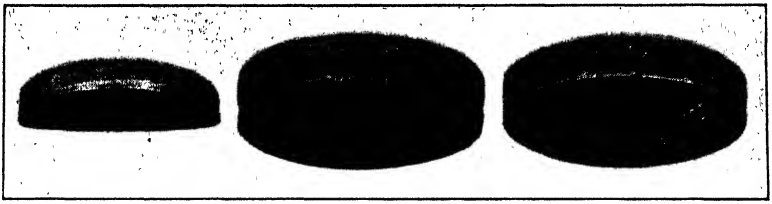
break. The counterpart of this illustration in practice is shown in Fig. 22. It is part of a disc blanked from ¼-in. soft steel in a die having proper clearance for material of such ductility. Note that the white burnished band around the disc shows the depth which the disc had penetrated into the die (Fig. 21 *B*), when plastic deformation ceased and the fractures started. The remainder is a typical, clean-fractured surface showing irregularities due to the different angles of the cleavage planes on which failure occurred in the many crystals. The crystalline structure and the space lattice of such material were shown in Figs. 8 and 9.

The sketches *D*, *E* and *F* in Fig. 21 and the disc shown in Fig. 23 illustrate the ragged sort of a fracture which may be obtained if there is clearance between the punch and die, but not enough to suit the angle

at which material of such ductility tends to shear. Note at *D* and *E* that the fractures which start from the opposing cutting edges do not meet but leave a connecting ring of metal which must be sheared again as shown at *F*.

Fig. 24 shows a disc of harder, smaller-grained, cold-rolled material blanked with the same punch and die as the disc shown in Fig. 23. Note, however, that the fracture is clean and the penetration to effect shearing was very much less. As illustrated at *G* and *H*, Fig. 21, the plastic deformation before the fractures started was very little, and the break was completed in a much shorter distance than in the previous case.

Considerable space was devoted in Chapter II to showing the relation between hardness, strength, crystal size and ductility. In blank-



22 23 24

FIG. 22.—Low-carbon steel and ample clearance, showing penetration or reduction in thickness before fracture and surface curvature due to tensile strains during plastic deformation.

FIG. 23.—Half-inch hot-rolled mild steel blanked with insufficient clearance and showing secondary fractures.

FIG. 24.—Hard steel showing small reduction in thickness and clean fracture though clearance was the same as for Fig. 23.

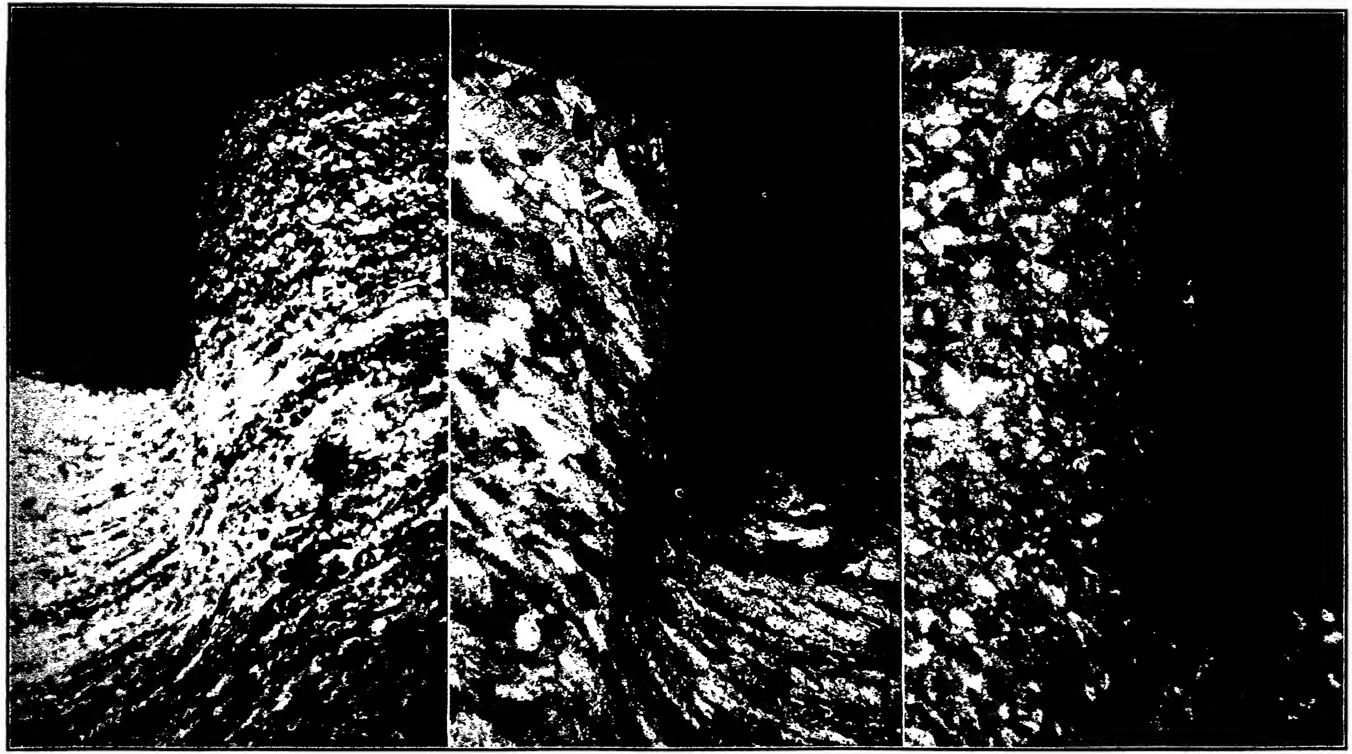
ing, the depth of penetration to effect shearing seems to fall in the same category as a measure of ductility and in inverse proportion to the hardness. The per cent reduction in thickness in shearing with suitable clearance seems related to the per cent reduction in area in the tensile test, although no proof of it is available at present. A comparison of hardness and depth of penetration for the three discs shown in Figs. 22, 23 and 24 shows that, as the hardness increases, the depth of penetration to effect shearing (and therefore the ductility) decreases. Thus the penetration was approximately 30 per cent for Fig. 22 with a Shore Scleroscope hardness number of 19; 16 per cent for Fig. 23 with a hardness number of 21, and 8 per cent for Fig. 24 with a hardness number of 26.

Fig. 25 shows three photomicrographs of metal which have been partially sheared through to confirm Fig. 21 and to show details of the crystal structure where the cut begins. The sample selected was partially strain-hardened Tobin Bronze strip ¼ in. thick. The shearing punch was forced to enter about 17 per cent of the way through the strip. At that point the beam of the testing machine had just begun to drop, indicating that the maximum pressure had just been passed.

The sample was then cut in quarters along lines running with and across the length of the strip or the direction of rolling. The cross-sections were polished, etched and photographed at magnifications of 90 and 100 times their actual size. Fig. 25 *A* was taken at the point indicated by *x* and a circle in Fig. 26, on a surface with the direction of rolling. It is etched to bring out flow lines and to verify the plastic metal movement which takes place before the fracture really starts, as was illustrated in Fig. 21 *B*. Note the manner in which the top surface of the metal had been dragged down by the tensile strains in the metal as the punch progressed.

Fig. 25 *B* and *C* illustrates an interesting point relative to the "grain" of rolled metal. As the rolling is (ordinarily) all in one direction, the original crystals, which tend to start out more or less spherical or equiaxed, are flattened down and worked out in the direction of rolling. This is illustrated by photo *B*, which is a cut with the "grain" and shows generally elongated crystal outlines as compared with photo *C*, which is a cut across the "grain" and shows generally smaller and equiaxed grain sections.

The elongation of the crystals has been accomplished by movement along many slip planes which are favorably located with respect to the rolling action. Other slip planes at other angles have not been used, however, suggesting a probable difference in physical properties of the strip with and across the grain. Thus the upper surface of the strip has been dragged down much more in photo *B* than in *C*. This and the fact that no appreciable fracture has yet started in *B* where the edge of the punch is cutting across the grain indicates that the metal is in a more plastic state and can be worked further before reaching the ultimate strength. In photo *C* the cutting edge is with or parallel to the grain, in which direction the metal has less remaining plasticity and fractures more quickly. To show this, note that the punch has traveled a considerable distance beyond the lower end of the smooth or burnished surface and has opened up quite a wide fracture. This fracture in fact has traveled almost a third of the way through the remaining thickness of the strip.



A B C

FIG. 25.—Tobin bronze 17 per cent sheared as at X in Fig. 26, showing profile and stressed area. A, with the grain, indicates metal movement, $\times 90$. B, with the grain, and C across the grain ($\times 100$) show directional effect upon the crystals and upon the resistance of the metal.

Fig. 26 indicates in a general way the strains occurring in the metal in shearing. The fracture diagrammed in Figs. 21 and 22 really is a tensile failure. The strain along the surface is in tension, as shown by the dragging down of the free edges, Figs. 21 and 25. Such strains also leave their mark on the surfaces in contact with the flat faces on the punch and die owing to the slight movement of the material an appreciable distance back from the cutting line (Fig. 25 *C*). The tensile strains along the free surfaces result in a flaking off of the surface scale on unpickled material, back as far as the movement in the metal is appreciable. This is shown on the surface of the disc in Fig. 23. This flaking of hard scale (iron oxide or silicide) is obviously detrimental to the dies on account of its abrasive character and is sometimes retarded by coating the material with baked lubricating enamel or with copper or lead

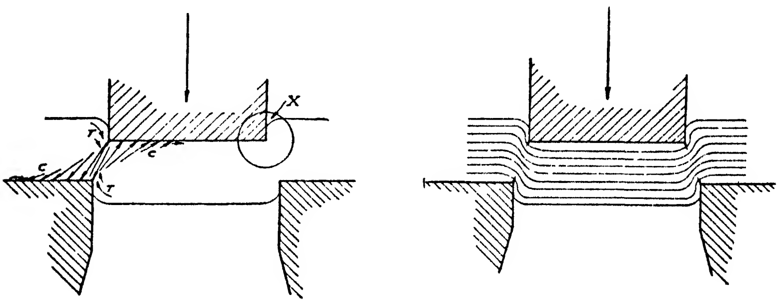


FIG. 26.—The compressive stress (and attendant tensile strain in the metal) between punch and die which distorts the sheet and crowds adjacent punches.

from a lead acetate or hot copper sulphate dip, though the latter methods are rather expensive.

There is also a compressive strain due to the diagonal pinching of the metal between the approaching faces of the punch and die. This is a considerable force and has an outward component which is responsible for the crowding of metal between punches, and the distortion of perforated sheets.

Working Pressure.—The pressure required to cut a given blank varies according to the tools: the clearance between the punch and die, the sharpness of the cutting edges and the angle of shear on the punch or die.

For round work, clearance is half the difference between the diameter of the die and the diameter of the punch. For any shape it is the distance between the punch and the die when the punch is entering the die centrally. Something of the effect of the clearance upon the type of fracture was shown in Figs. 22 and 23. Fig. 27 is a reproduction of

three indicator diagrams showing variation of punching pressure with clearance taken from a report presented before the A.S.M.E. by Professor Gardner C. Anthony. The material was mild steel plate, 0.315 in. thick, showing a quite uniform reduction of thickness at fracture of 34 per cent, as shown by the peak of the curves. The diameter of the die was 0.767 in. Three punches were used having diameters of 0.702 in. for card *A*, 0.738 in. for card *B* and 0.750 for card *C*. As the clearance between the punch and die was decreased, the pressure required for fracture was increased. Thus the clearance was 10.3 per cent of the metal thickness for card *A*; the punching pressure was approximately 32,000 lb. For card *B* the clearance was 4.6 per cent of the metal thickness and the punching pressure was 33,000 lb. For card *C* the clearance was 2.7 per cent, and the pressure was 34,500 lb. In pounds per square inch on the original area this pressure to effect shearing varied approximately from 42,200 to 44,400, about 5 per cent.

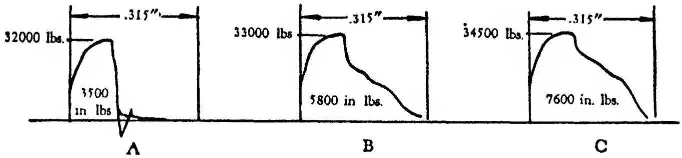


Fig. 27.—Indicator diagrams show progressive load in punching ¾-in. holes through ductile 5⁄16-in. boiler-plate with (*A*) 10, (*B*) 5 and (*C*) 3 per cent clearance, approximately. (*Anthony*)

Dull cutting edges increase the shearing pressure and greatly increase the working distance to complete the shearing action. In an experiment at the University of Toledo in 1935 several metal samples were punched, first with sharp dies and then with the same dies dulled with a stone to nearly 1⁄64-in. radius. For example, in punching ⅛-in.-thick hot-rolled (soft-temper) steel with the die sharp the maximum pressure was 40,000 lb. per sq. in.; penetration to effect shearing about 48 per cent; work done (area under stress-strain curve) 1.01 in.-tons. With the die edges dulled, the maximum pressure increased to 46,000 lb. per sq. in.; penetration to nearly 70 per cent, and work done, to 1.66 in.-tons. That is, the dull cutting edges increased the working pressure about 15 per cent and increased the work or energy requirement about 64 per cent.

Note the effort to illustrate the formation of burrs in sketch *J*, Fig. 21. As has been pointed out, a sharp edge causes fractures to start in the crystals of the line of severely strained material in contact with it when the limit of strength is reached. If an edge is worn rounded or chipped in spots, the surface area of severest strain is not localized along

a line but has considerable width. The natural tendency is for the fractures to start approximately from the point where the edge radius joins the vertical side of the punch or die. If there happens to be a weak spot or more favorable cleavage plane nearby, the fracture will start there, accounting in part for the irregularity of burrs.

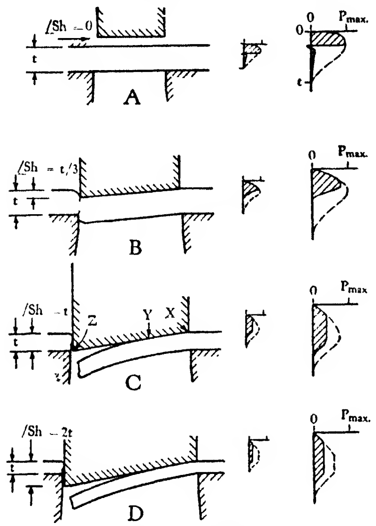


FIG. 28.—Different angles of shear on the punch (or die) reduce the work it is doing at any instant. Note Fig. 29.

Return now to the effect of sheared dies upon shearing pressure, a discussion in which there is an opportunity for confusion in terms. We are applying the verb "to shear" to the act of cutting metal in dies. The noun "shear" applied to dies, or "angular shear," $\angle$ *Sh,* refers to the practice of grinding the face of the punch or die at an angle or otherwise setting one cutting edge at an angle with reference to the other. The object, of course, is to reduce the amount of resistance which the punch or upper blade is encountering at any one instant. The length of the working stroke is increased, but the metal is actually sheared just a little at a time.

Fig. 28 is arranged to show diagrammatically the effect of shear on the dies, and Fig. 29 to show the variation in pressure for typical conditions.

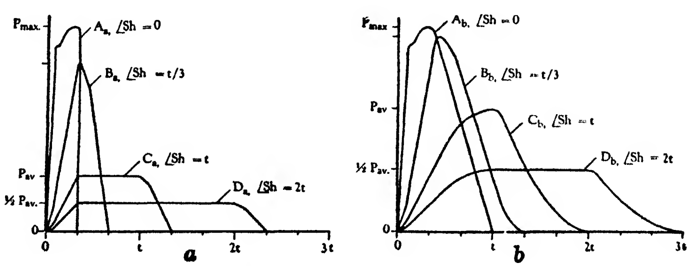


FIG. 29.—Comparative punching pressure charts for conditions of shear illustrated in Fig. 28, with ample clearance in group *a*, and insufficient clearance in group *b*.

At 28 *A* with a flat punch and die the shear is equal to zero, $\angle Sh = 0$. Assuming that there is ample clearance to give a clean fracture, the rise and fall of the working pressure, as the punch passes

through the metal, is as illustrated by the curve A in Fig. 29 a. This is based upon ductile metal requiring about a third penetration, or reduction in thickness, to effect shearing. Thus the pressure rises quickly to the elastic limit, then gradually to a peak at the point of fracture a third through the metal, and drops at once to nearly zero. Such a sudden drop will cause more or less oscillation in the press frame.

The curve at A in Fig. 29 b shows the same metal sheared in a die with insufficient clearance (see Figs. 21 F and 27 C), a common condition. The principal difference between this and the previous case is that considerable pressure is required, after the primary fracture, to take care of secondary fractures and higher friction. This materially increases the average pressure over the distance equal to the metal thickness (t).

Fig. 28 B shows a punch with shear equal to the penetration to fracture, that is, $\angle\ Sh = t/3$ in this case. In the position in which it is drawn, the first portion of the punch to enter has reached the peak load and is starting the fracture, while the last part to enter is just starting to work. This is the position of greatest total pressure under the prevailing conditions, as shown by curve B in Fig. 29 a. This greatest pressure is equal to the average of the pressures from the start to the peak on curve A, and therefore is not materially lower than that peak. The advantage of this amount of shear is that the pressure builds up and is released more gradually than in the case of the flat punch (A).

In Fig. 28 C the punch has shear equal to the metal thickness, $\angle\ Sh = t$. In the position shown, the punch is just coming in contact with the metal at x, the starting pressure; at y it is starting the fracture, the maximum pressure; and at z it is entirely through. With sufficient clearance the pressure between y and z is practically zero. In any case, the greatest total pressure (x to z) is equal to the average value of the pressure on the flat punch during its progress through the metal.

This *average pressure* is nearly a third of the maximum pressure for the one-third penetration metal with ample clearance, case 29 a (P average = approximate P maximum $\times$ 0.33). It is lower for less ductile metals requiring less penetration to effect shearing. It is higher where the clearance is insufficient, as in 29 b.

If the shear is increased to twice the metal thickness, Fig. 28 D ($\angle\ Sh = 2t$), then only half the length of the cutting edge can be in the metal at any instant. Consequently the greatest pressure on the punch is only half the average pressure just discussed. The pressure curves are as shown at D in 29 a and 29 b, depending upon the clearance.

It is apparent, from the foregoing, that, wherever the shear is equal to or greater than the thickness of the metal ($\angle\ Sh = t$ or greater), the

working pressure (P) is lower than the average pressure ($P_{av.}$) according to the ratio of the metal thickness (t) to the shear ($\angle\ Sh$). That is:

$$P = P_{av.} \times t \div \angle\ Sh \tag{1}$$

$$P_{av.} = P_{max.} \times \text{per cent penetration} \tag{1a}$$

Without shear, when $\angle\ Sh = 0$, $P = P_{max.}$ (See Appendix, Chart II.)

Referring to the three curves shown in Fig. 27, the *average pressure* ($P_{av.}$) varies from 35 per cent of the peak pressure ($P_{max.}$) with proper clearance and ductile material, to 65 per cent of the peak pressure with insufficient clearance. The average pressure is probably as low as 15 per cent or less of the peak pressure for hard metals with ample clearance.

The *maximum pressure* to shear any shape with a sharp flat punch and die with proper clearance is obtained by multiplying the length of cut (L) in inches, that is, the circumference or perimeter of the shape, by the thickness of the metal (t) in inches, which gives the cross-section area (A) in square inches, to be sheared. This is multiplied by the ultimate shearing strength, or resistance to shearing for the metal (S_S) in pounds per square inch to give total peak pressure ($P_{max.}$) in pounds. Combining this:

$$P_{max.} = L \times t \times S_S \tag{2}$$

or

$$P_{max.} = \pi \times d \times t \times S_S \tag{2a}$$

(See Table II and Appendix, Chart I.)

Summary of Factors Affecting Pressure.—The pressures obtained graphically from the nomograms furnished in the Appendix can be read closely enough for press calculations. The peak pressure, $P_{max.}$, which is the value obtained from Chart I, is used without modification in many cases, especially on work of comparatively small dimensions. Those factors which change it may be reviewed as follows:

1. Clearance, between the punch and die. This affects the pressure most when the punch diameter is small compared to the metal thickness. The peak pressure may be increased possibly 5 or 10 per cent by decreasing the clearance from an amount suitable for a clean fracture to nearly zero. Increasing the clearance above what is necessary for a clean fracture decreases the load somewhat and increases the angle of the fracture and the rounding over of the free edge.

2. Sharpness of the cutting edges. A sharp edge localizes the severest stresses and causes the fracture to occur sooner and more easily than a dull edge. The condition of the edges affects the pressure most when the metal is thin.

3. Hardness of the material. Cold-working, and strain-hardening by cold-rolling, may increase the resistance to shearing up to perhaps 100 per cent under ordinary circumstances.

4. Shear on the punch or die. As a flat punch progresses through metal it meets an increasing resistance up to the ultimate strength and then a more or less sudden drop. If the punch or die is ground at an angle such that there is a difference in level between the high and low points equal to the metal thickness, then the greatest punching pressure is reduced to the average or mean of the progressive pressure through the metal, as has been described. If the shear is increased to twice or three times the metal thickness, the punching pressure is reduced to a half or a third of the average pressure. Shear is most important on blanks which are large compared with the metal thickness.

The energy required to perform the work of shearing is the product of the average pressure and the working distance:

$$W = P_{\text{av.}} \times t \qquad (3)$$

or

$$W = P_{\text{max.}} \times \text{per cent penetration} \times t \qquad (3a)$$

(See Appendix, Chart III.) Work and energy are measured by the area under the pressure-thickness curve. In Fig. 27 it may be noted that the energy requirement (in inch-pounds) increases as the clearance is decreased. The harder, less ductile metals require pressure through a shorter distance, and accordingly less work is performed in shearing them. Shear on the punch or die reduces the working pressure but increases the distance through which it must be applied, so that the total work done is the same, as indicated in Fig. 29.

Press power-requirements are summarized briefly in the Appendix in connection with Chart X and Table XXIV.

Speed of operation depends upon the method of feeding and upon the impact and heating which the cutting edges of the punch and die steels will stand with economic life. The heating depends upon cutting speed, lubrication, die clearance and press deflection. The impact depends upon the speed and stroke of the press which determines the velocity at shearing, and upon the resistance of the material to shearing, per unit length of cutting edge. A more detailed consideration of the subject of operating speeds will be found in Chapter XIV.

Shearing Resistance.—Table II gives values for the shearing resistances (S_S) of common materials, both annealed and in a more or less strain-hardened state, and the penetration to start the fracture. It is compiled tentatively from experiments and from such meager published data as we have found.

It may be noted that, where shearing tests are available on pure

metals, values for their alloys will be higher, as suggested by Fig. 12. Thus in Table II the shearing resistance offered by brass is materially greater than that for either of its constituents, copper and zinc. Values for the shearing resistance of annealed aluminum as given by "The Aluminum Industry," Vol. II, are:

for 99.9 per cent purity 7000 lb. per sq. in.
for 99.2 per cent purity 10,000 lb. per sq. in.

TABLE II

RESISTANCE OF METALS TO SHEARING IN DIES

Material	Annealed State		Partially Cold-worked[a]	
	Resistance to Shearing, S_s, Lb. per Sq. In.	Reduction, or Penetration Per Cent	Resistance to Shearing, S_s, Lb. per Sq. In.	Reduction, or Penetration Per Cent
Lead	3,500	50	Anneals at room temperature	
Tin	5,000	40	Anneals at room temperature	
Aluminum	8,000	60	13,000	30
Zinc	14,000	50	19,000	25
Copper	22,000	55	28,000	30
Brass	32,000	50	52,000	20
Bronze 90–10	....	....	40,000	
Tobin bronze	36,000	25	42,000	17
Steel 0.10 C	35,000	50	43,000	38
0.20 C	44,000	40	55,000	28
0.30 C	52,000	33	67,000	22
0.40 C	62,000	27	78,000	17
0.60 C	80,000	20	102,000	9
0.80 C	97,000	15	127,000	5
1.00 C	115,000	10	150,000	2
Silicon steel	65,000	30		
Nickel	35,000	55		
See also Table XXVII in Appendix				

[a] As received. Actual "degree of cold working" due to previous treatment unknown.

Available test data do not agree closely. This table is subject to verification with closer control of metal analysis, rolling and annealing conditions, die clearances, etc.

Note that "per cent reduction in area" is considered to mean the same thing as "per cent reduction in thickness to effect shearing."

This merely indicates the considerable differences possible due to even small amounts of other elements.

The opinion has been expressed that the shearing resistance of metal bears a fairly constant relation to its (nominal) ultimate tensile strength from about 75 per cent in the annealed state to around 50 per cent when

severely strain-hardened. This seems to have applied fairly consistently in many tests of aluminum. Table I for Tobin Bronze, however, shows relations of 60 and 65 per cent, annealed and strain-hardened. It should be noted that neither shearing nor common tensile tests give a true unit stress, and that the two are affected in different ways by strain-hardening.

The columns in Table II, which show values for cold-worked material, have inconsistencies due to non-uniformity in the extent of cold-working. That is, some samples may have been "half hard," others "quarter hard," etc., or, according to non-ferrous ratings, two, four or eight gauge numbers hard, according to the amount of rolling undergone since the last annealing. A table could undoubtedly be prepared eventually taking these differences into account. There is suggested, however, the need for a common method of rating strain-hardening from an absolute zero. Further data along this line will be offered later, but some which applies particularly to shearing may be recorded here.

Figs. 30, 31 and 32 show stress-strain curves (the heavy solid lines) drawn by an Olsen recording testing machine in the course of punching tests upon various samples of aluminum, steel and high brass. The curves have been translated to show the actual stress in pounds per square inch upon the continually diminishing cross-section area of material in shear. Finally the new curves have been transposed to new positions in an effort to indicate a curve or line which would be the locus of all curves of plastic deformation of the material in whatever state. This curve indicates the rate of strain-hardening as the metal is worked between its initial yielding and final failure.

The punching or shearing test offered sufficient data in usable form. Round punches and dies were used, with the clearance between punch and die maintained at about 10 per cent of the metal thickness in order to give clean fractures without the confusing influence of secondary shearing. Referring back to Fig. 21 *B*, which illustrates the progress of a sharp-edged punch through sheet material, it will be remembered that the stresses are not perfectly uniform across the area under stress, but are most severe at the corners. Referring to Fig. 26, in which are indicated the directions of tensile and compressive strains in material being punched, it will be noted that the tensile stresses are not quite parallel to the direction of travel of the punch. Both of these considerations account for discrepancies in the results obtained. Nevertheless, the test is, in effect, plastic deformation in tension with controlled and measured necking-in or reduction in area. The curves used were the results of single tests, checked, however, by comparison with other tests on the same piece of material.

Fig. 30 shows two curves taken from shearing or punching tests performed upon 99.8 per cent pure aluminum. Punch diameter is 1.551 in.; die diameter, 1.591 in., metal thickness, 0.162 in. The metal was first tested in the cold-rolled condition, as received, producing curves of which X_1 is typical. A portion of the same piece was then annealed at 850 to 900° F. and tested, the curve Y_1 being a typical example.

The curves X_2 and Y_2 were computed and plotted from X_1 and Y_1, to show the stress per unit area on the area actually in shear at each instant. This is quite easily done by proportion and comparison of penetration with total thickness. Wall friction was neglected. The curves were then transposed to the right so that plastic deformation

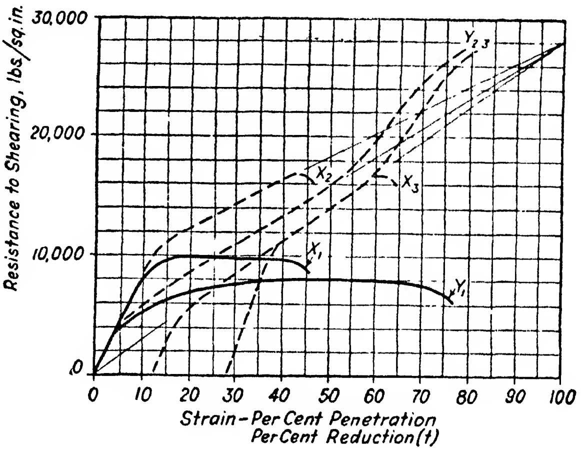


Fig. 30.—Punching tests of pure aluminum, as received or rolled (x) and annealed (y) with derived curves showing resistance per *unit of area* and the hypothetical strain-hardening curve.

curves, above the "elastic limit," form a continuous curve from the origin. The hypothetical first portion of this curve would apply to perfectly soft and plastic material, perhaps approaching zero yield point in the single crystal state. It is possible according to this hypothesis to grade the annealed material as about 13 per cent strain-hardened (on the absolute scale) and the cold-worked material as about 28 per cent strain-hardened. In such a case, given the initial state and the amount or percentage of cold-working to be performed, the resultant condition of the metal should be reasonably predictable.

In Fig. 31, the curves L_1, M_1 and H_1 are the results of shearing tests on annealed samples of low-, medium- and high-carbon steels, respectively. It will be found interesting to compare these with the tensile

test curves for annealed steels of different carbon contents, shown in Fig. 14. Note in this case also the position of the curve for 0.15 C steel partially cold worked. If amount of cold-working and absolute stress could be incorporated here, the two curves for 0.15 C steel should coincide in the latter part of the range, as in Figs. 30, 32 and 125.

Returning to Fig. 31, the curves L_2, M_2 and H_2 are merely replottings of the originals to show absolute or actual stress per unit of changing area instead of beam pressure (total, or per unit of original area). The plastic deformation portions of these curves are then transposed to coincide with straight lines through the origin in the same manner as in Chapter VII, and especially Fig. 122. The difference in carbon content then grades these metals as having rates of strain-hardenings (S_x, Fig. 125) of about 112,000, 138,000 and 270,000, respectively. The results, however, are probably not comparable, on account of stress differences between the shear, tensile and compressive tests, and localized high stresses at the cutting edge.

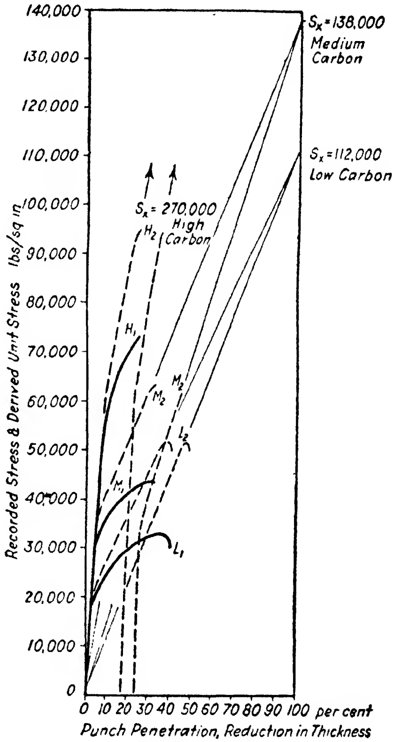


FIG. 31.— Punching tests of low (L), medium (M) and high (H) carbon steels with derived absolute curves, and hypothetical strain-hardening curve.

Fig. 32 shows shearing tests of No. 11 gauge, 0.125 in. yellow brass. Curve A is from No. 8 hard or spring temper brass as rolled, measuring 91 Rockwell B scale or 190 Brinell, which failed at about 54,000 lb. per sq. in. and 22 per cent penetration. Curve B is from the same material partially annealed. Curve C is again the same material annealed at 1100° F. for ½ hr. to a Brinell hardness of 58. It failed at approximately 34,000 lb. per sq. in. and a punch penetration of 49 per cent.

The three recorded curves have been replotted at A_1, B_1 and C_1 to show the actual rise in resistance as the area in shear is reduced and the material in the pressure area is distorted and strain-hardened. These new curves were then transposed to the right with a correction of angle,

to indicate the continuous rate of strain-hardening. The blanks produced in these tests are shown in Fig. 20. It will be noted here again that the hardest blank shows the narrowest burnished band around the edge. The softest shows the greatest distortion or bowing.

The use of rate of strain-hardening curves developed from the shear test, Figs. 30, 31 and 32, are principally of interest to show trend and to

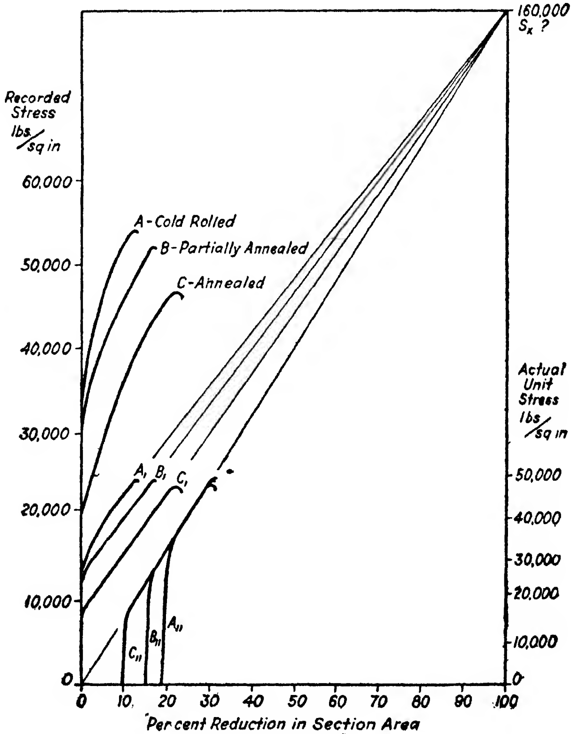


FIG. 32.—Shearing or blanking test curves of 70 : 30 brass: *A* No. 8 hard, *B* partially annealed, *C* annealed; then relocated at A_1, B_1 and C_1 to read in unit stress as the area is reduced; and finally transposed to establish a common curve for any state.

illustrate the effects of hardness upon load. More satisfactory results for purposes of rating were obtained later from direct tension and compression tests as developed in Chapter VII.

Die Design Data.—Dies for operations in the shearing group vary in design and arrangement according to the particular operation, the press, the method of feeding and discharging, the quantity to be produced, the accuracy required and the whim of the designer. It is beyond the scope of this discussion to go into mechanical details of die

designing, arrangement and proportioning, as it would involve the consideration of too many alternatives and possibilities. Such details have already been discussed quite well.[1]

Tools for shearing operations ordinarily consist of a punch or male member attached to the moving slide of the press, and a die or female member attached to the fixed bed of the press. The arrangement is inverted in some cases, as in Fig. 36. A single unit may consist of a number of punches and dies mounted on common holders and operating simultaneously. Other essential adjuncts to the tools include gauges, pilots and guides for the stock, strippers to prevent the sheet clinging to the punches, knockouts to lift punchings out of the dies when they are

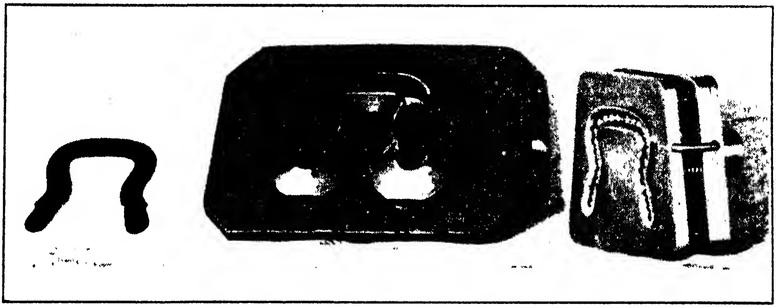


Fig. 33.—Simple blanking die with spring stripper, no guide pins.

not pushed through, etc. Some of these parts have been labeled in Fig. 40.

Figs. 33, 34, 36, 39 and 40 show blanking and punching dies of quite different types and constructions to illustrate a few of the features being discussed.

The time required of the die-setter to place the tools properly in the press depends upon how convenient the arrangements for holding the tools may be, and how accurately the tools must be located both in the press and relative to each other. Accuracy and convenience in tool setting are often closely related in that the holders are arranged to maintain the proper relative location while being set in the press as a unit.

The simplest sort of temporary tools may have plain plates for holders, Fig. 33, or no holders at all. They usually require quite a bit

[1] Die design detail references: Woodworth, "Punches, Dies and Tools for Manufacturing in Presses," Henley; Jones, "Die Design and Die Making Practice," The Industrial Press; Stanley, "Punches and Dies," McGraw-Hill; Woodworth, "Dies—Their Construction and Use," Henley; Dowd and Curtis, "Punches, Dies and Gauges," McGraw-Hill; C. W. Lucas, "Press Work Pressures," McGraw-Hill.

of fussing on the part of the die-setter to get them clamped up in position.

Watchmakers at an early date developed sub-presses, such as that shown in Fig. 34, to solve the set-up and accuracy problem. Holders of a more or less standardized design were constructed, and in these the punches and dies were kept set and ready to place in the press at any time. This act is quickly accomplished as relatively high die space presses are used with a punch stem T-slotted to receive the standard button on the top of the sub-press plunger and provision on the bolster for clamping the standard sub-press frame. Accurate alignment of the plunger in the frame is maintained by compressing a tapered babbitt bushing or sleeve in the upper part of the frame by means of the large flange or nut. The punch and die are held securely in the plunger and frame, and as they are set in place by the diemaker on the bench, no production time is lost at the press.

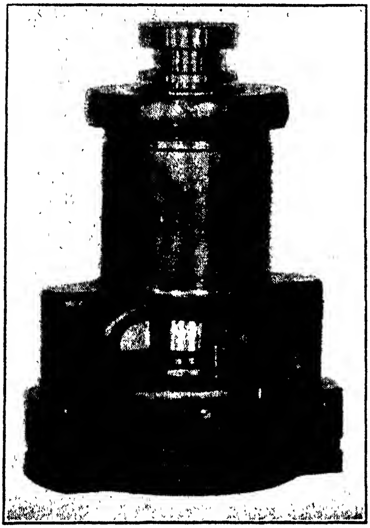


FIG. 34.— Sub-press die for watch parts and similar small clearance work on thin metal.

On larger operations on which the metal thickness permits greater clearance, but where the quantity to be produced is still large, the standardized die-set has become quite popular. These, as shown in Figs. 35 and 40, consist of steel or iron die base and punch plate held in alignment by two to four substantial guide pins. The die base ordinarily has slotted ears for convenience in holding it to the press bed, and is of sufficient thickness so that the hardened-steel guide pins, which are a straight drive fit or a taper fit, can be held securely against possible deflection. The punch plate is usually fitted with a stem which may be clamped easily in the slide of the ordinary punch press, and has driven in it the hardened bushings in which the guide pins slide. To serve their purpose of maintaining the proper relative locations of the die and punch, it is clearly desirable that the sliding clearance on the guide pins in the bushings should be very small compared with the clearance between the punch and die, which is necessarily small. Guide pins are used too, in many large and special dies for both convenience and accuracy in setting up, as in the case of automobile-shop die, Fig. 36.

The quantity of parts to be produced determines how fine a job should be done upon the tools in the matter of simplifying the manu-

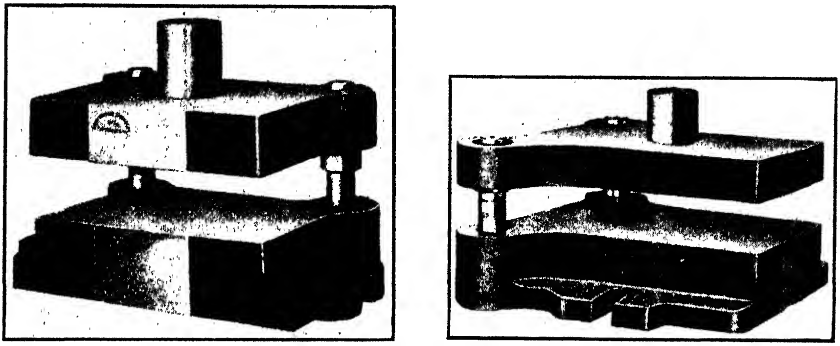


FIG. 35.—A standardized die-set including guide pins for accuracy and convenience in setting dies. *Courtesy Danly Machine Specialties, Inc.*

facture of parts subject to wear and providing rapid and easy regrinding and replacement of such parts. We are reminded of an equipment

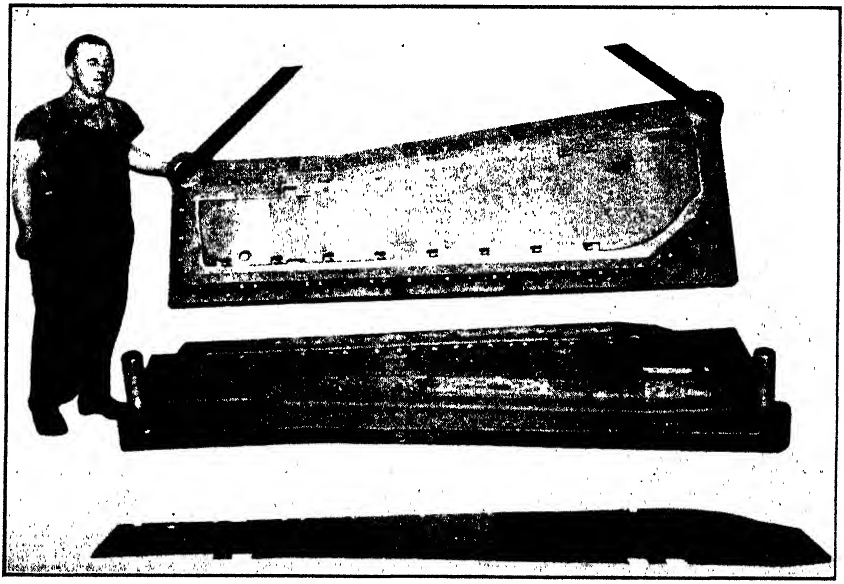


FIG. 36.—An inverted type blanking and piercing die for a running board. Guide pins, sectional cutting steels, spring knockout pad.

including master tools and fixtures made at very considerable expense so that punches and dies, accurate to a fraction of a thousandth and

absolutely interchangeable with any others made from the same masters could be produced ultimately at a remarkably low cost. These dies, perforating and blanking rather high carbon steel at over 350 strokes per minute, show what is at present a remarkable life of up to and over 700,000 working strokes per grinding.

Shear on dies, that is, grinding the punch or die at an angle, has already been discussed. It must be remembered, of course, that shear has a distorting effect as indicated at *C* and *D* in Fig. 28. Accordingly, when punching out openings in a sheet or article which must be kept flat, the die should be ground flat and the shear should be on the punch as indicated at *A* in Fig. 37. Conversely, in cutting out blanks which must be flat, from strip material, the punch must be flat, and any shear ground on the die so that the distortion is in the scrap only. It is desirable, of course, to have the shear balanced, as illustrated, so that there will be no side thrust tending to make the die creep and reduce the clearance on one side or deflect the punch.

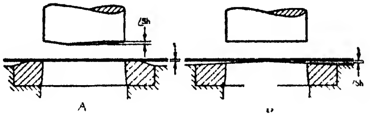


FIG. 37.—Shear on hole-cutting punch (*A*) to leave sheet or article flat; or shear on blanking die (*B*) to leave blank flat and distortion in the scrap.

Die Clearance.—The amount of clearance to be allowed between the punch and the die is still open to some question. There is an old rule of thumb that the clearance (half the difference between the punch diameter and die diameter) should be a tenth (0.10 t) of the metal thickness for soft material and up to an eighth (0.125 t) for hard material. Another rule gives 5 per cent of the metal thickness (0.05 t) for brass, 6 per cent (0.06 t) for soft steel and 7 per cent (0.07 t) for hard steel. Yet we have data showing clearly, so far as minimum pressure, minimum work and a clean fracture are concerned, that a soft ductile metal requires more clearance than hard metal. The explanation of the reverse order in the old rules is undoubtedly that hard metal will stand more clearance than soft metal though it does not require it, and the larger clearance reduces the load on the cutting edge. The author believes that the clearance should be expressed in a relative proportion to the ductility of the metal as indicated by the per cent reduction in area in the tensile test or the per cent reduction in thickness in shearing. The card *A* in Fig. 27 was taken on comparatively ductile steel showing about 55 per cent reduction in area, 34 per cent reduction in thickness and requiring not less than 10 per cent clearance for a clean fracture. On the other hand, the blank shown in Fig. 24, showing about 8 per cent reduction in thickness, fractured cleanly with under 3 per cent clearance.

Table III and Fig. 38 show the figures and curves obtained in a

standard blanking test using a series of punches to give different clearances. The blanking pressure falls as the clearance increases. Bowing of the blank increases with the clearance. Secondary shearing, as evidenced by jagged lips around the fractured edge of the blank and by the recorded curves, becomes less as the clearance increases, and disappears when it amounts to 10 per cent of the metal thickness. No burrs were apparent in any test. The work done, represented by the area under the curves, becomes less as the clearance increases. These tests were performed in an Olsen recording testing machine fitted with a small Danly die set, one die and a series of interchangeable punches of different diameters. The 45° line on the charts is for reference purposes in judging the decrease in secondary shearing and work.

The upper limitation on the amount of clearance is the greater tendency to form burrs. Thus, especially if the cutting edges are not sharp and the clearance is excessive, the fractures may start above the cutting edge in the tensile stress region, as indicated at the right in sketch *J* of Fig. 21. Increasing the clearance does reduce the crowding or spreading action in the metal which occurs during the plastic deformation period as illustrated in Fig. 26. This spreading side-thrust is of considerable intensity at short range, in proportion to the metal thickness, and tends to bend delicate punches, Fig. 52, which are close enough,

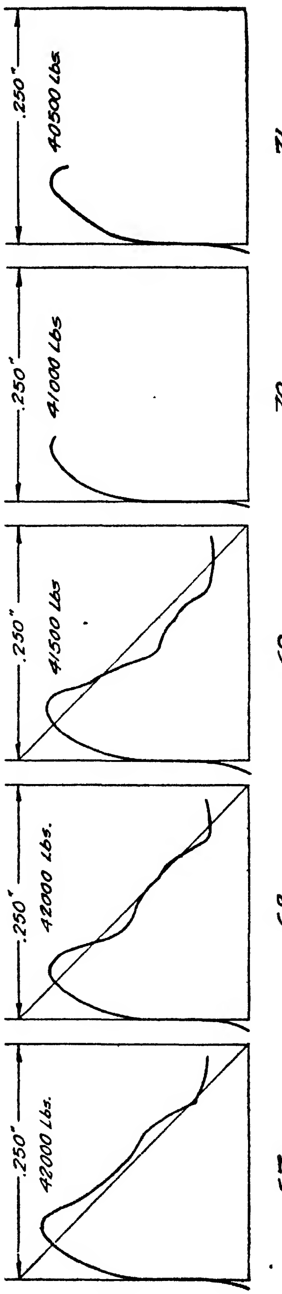


Fig. 38.—Standard blanking test curves as recorded for ¼-in. C.R.S. soft temper, with die clearances of 2.8, 6, 8, 10 and 14 per cent respectively. See Table III.

causing them to alter their clearance and in some cases to break or chip against the die edges. Where a number of small punches are grouped closely around a large punch, it is usually desirable to grind the small punches shorter than the large one by an amount equal to the reduction in thickness to effect shearing. The object is that the small punches shall not enter the metal until after the spreading, due to the entry of the large punch, has taken place.

TABLE III

EFFECTS OF CLEARANCE IN BLANKING COLD-ROLLED STEEL, SOFT TEMPER 0.250-IN. STOCK THICKNESS

Test No.	Diameter of Punch, Inches	Clear-ance on Side, Inch	Per Cent Clear-ance	Pressure, Lb. per Sq. In.	Actual Pressure, Pounds	Bow in Blank, Inch	Notes
67	1.577	0.007	2.8	33,600	42,000	0.010	Secondary Shearing
68	1.561	0.015	6.0	33,600	42,000	0.0115	Secondary Shearing
69	1.551	0.020	8.0	33,200	41,500	0.012	Secondary Shearing
70	1.541	0.025	10.0	32,800	41,000	0.015	Best clearance
71	1.521	0.035	14.0	32,400	40,500	0 021	

NOTES: 67, 68, 69, perceptible burrs; 70, 71, imperceptible burrs. Penetration to effect primary shearing: average 35 per cent. Diameter of hole in die: 1.591 in.

Table reproduced through the courtesy of M. J. Mattera of the E. W. Bliss Co., Oct. 25, 1928.

Sheared blanks may be either pushed through the die, Fig. 33, or pushed back out of the die, Fig. 36, and discharged or carried off from its surface. In the latter case the walls of the die are straight and perpendicular to the plane of the surface all the way down. As the die is ground down, the shape and dimensions of the piece which is cut remain the same.

In some cases the walls are made straight even though the blanks are pushed through the die. When this is done the solid mass of blanks fits so tightly in the die that often more pressure is required to push them down than is needed to shear the blank. It is desirable in such cases to lap the die walls vertically. It may be noted here that blanks sheared with insufficient clearance, as shown at *F* in Fig. 21, present jagged edges to the die wall, increasing the push-through resistance and the wear. There is said to be some tendency for straight-wall dies to wear bell-mouthed at the top.

Most dies, particularly for cutting steel, are made with a straight

wall for only a short distance, as shown in Fig. 21 and in the section of the die at *D* in Fig. 39, and then are flared larger at a $\frac{1}{2}°$ to $2°$ angle so that the blanks will fall freely. The disadvantage of this practice is that, if the die is ground down beyond the straight portion, the size of the blank increases according to the taper. Also, as the taper is often put in by hand and is not uniform, the increase is not uniform. The difficulty is sometimes overcome by peening the die a short distance back from the edge so as to reduce the size of opening. This method is rather crude, especially if proper working clearance is to be maintained.

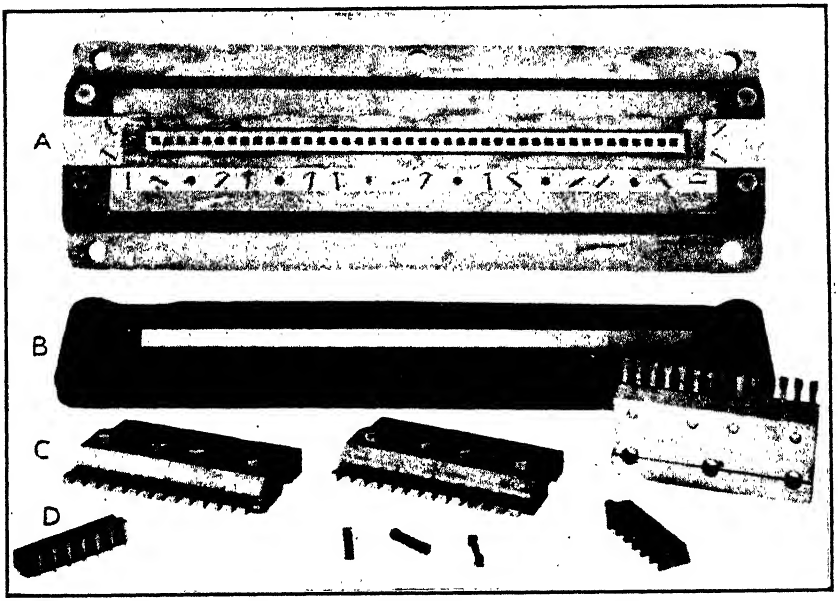


Fig. 39.—Perforating die, holder (*A*) with guide pins and with interchangeable die sections (*D*) wedge-clamped into place, cam-actuated stripper (*B*) riding on guide pins and fitting punches closely, and clamp type sectional punch holders (*C*).

It is noted in some cases that blanks pushed through the die, notably radio condenser plates, are slightly buckled, the trouble being overcome by blanking against a spring pad, returning the parts to the surface of the die and carrying them off in the scrap, or by using harder temper.

The act of shearing may be completed before the punch has progressed a quarter of the way through the metal or not until it is all the way through, as shown at *H* and *F* in Fig. 21. This depends upon the ductility and clearance. If the blank is to be lifted out of the die there is no need of going farther than enough to shear. In most cases, how-

ever, the blank is pushed through and the stock is slid across the face of the die. Accordingly the punch must enter the die slightly so that it will not leave the blank protruding. Many types of presses stretch or deflect as the working pressure builds up, owing to the elasticity of the materials of construction. If the push-through load is large, the deflection must be compensated for by setting the punch to enter farther into the die under no load conditions. Of course, if the deflection of the press is not in a straight line, so that the small clearance between the punch and die is lost, the cutting edges will strike and wear or chip.

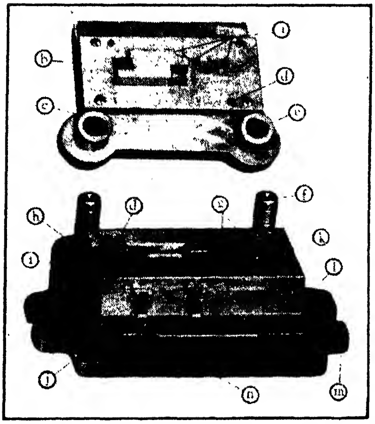


FIG. 40.—A follow type perforating die with parts labeled: (*a*) punches, (*b*) punch holder, (*c*) punch plate (standardized), (*d*) dowels, (*e*) guide pin bushings (standardized), (*f*) guide pins (standardized), (*g*) punch guide bushings, (*h*) fixed stock guide, (*i*) feeding space, (*j*) spring guides, (*k*) stripper plate (fixed), (*l*) die, (*m*) die base (standardized), (*n*) number and name plate.

Strippers and Ejecting Mechanisms.—After the punch has gone down through the metal it must be pulled back, and in this it is found that metal tends to hug the punch very tightly. It will be noticed in sketches *F* and *C*, Fig. 21, that the top "stratum" of the metal being sheared is pulled down plastically in tension alongside of the punch. When the strains in it are released by the fracture, it tends to spread out, and the raw edge is under pressure gripping the punch as the effort is made to withdraw. For this reason the punch should be ground smooth, and even lapped or polished lengthwise in extreme cases. For this reason also many punches are broken in stripping when the punch diameter is close to the metal thickness. All punches and punch holders must be arranged so that they cannot pull out on the up stroke.

To strip the metal off from the punches as they rise, strippers of various sorts are provided. These strippers are plates having suitable holes or openings through which the punches pass. Fixed strippers, Fig. 40, are attached to the die holder at a sufficient distance above the die surface to permit free handling of the stock. Spring strippers, Fig. 33, are attached to the punch holder and operated with springs under considerable tension. The face of the spring stripper is normally flush with the punches, although a small clamp is provided at the side in Fig. 33 for convenience in die setting. Five to 12 per cent of the maxi-

mum shearing load may be taken as representative of normal stripping pressures on (large) round punches. Cam-actuated strippers (*B* in Fig. 39) are independently controlled from the press shaft and are timed to hold the metal under positive pressure while it is being punched, as well as to strip it from the punches.

Several forms of ejecting mechanisms are used to force out of the dies, blanks which are not to be pushed through, thereby performing a service similar to that of strippers on the punches. Where the service is light, springs may be used, but where considerable pressure or special timing are required, fixed or cam mechanisms are employed. For dies on the press bed the mechanism is described as a lift-out and includes a cross-bar under the bolster-plate of the press directly connected to the slide by rods through the bolster-plate, or it may be a bell-crank under the bolster driven from a cam on the end of the press crankshaft. If the die is inverted on the slide, the mechanism is a knock-out and is operated by means of a cross-bar through the slide from fixed points on the frame, or it may be actuated by bell-cranks on the slide, carrying rollers which ride against cam pieces attached to the frame.

In the dies, the knock-out, lift-out or stripper takes the form of a plate fitted in the shape of the die or around the punches. If the plates are spring actuated, Fig. 36, the springs and the screws which limit the motion of the plate are contained right in the die or punch assembly. If the plates are actuated by an outside mechanism forming part of the press, the impulse is received through pins which pass through the holders and slide or bolster plate.

Guiding Devices.—The position of the material to be punched, relative to the die, is controlled on the simplest dies, Figs. 33 and 36, by the eye of the operator. As the speed of operation is increased and the amount of scrap or waste metal is reduced, mechanical means of location including various guides, gauges and pilots are required.

Guides to keep strip material in line with the dies may be strips along the dies, wire loops or wickets at each end of the dies, or strips or hardened rollers in the feeding mechanism. In some cases, where only a small margin of scrap is left, one guide on the die is fixed and the other is backed by springs to hold the strip material against the fixed guide, as in Fig. 40. The perforating die in Fig. 39 requires no guides as provision is made for this function in the table and grippers belonging to the feed.

Gauges for the location of previously blanked and/or formed work, and stop pins to limit the hand feeding of strip material, usually take the form of hardened pins set about the die. It is often necessary to arrange to prevent slivers of stock getting under the edge of these pins

or gauges, a troublesome thing especially likely to occur when a gauge is right at a cutting edge.

Pilots are used in many follow-dies, repunching and progressive operations to correct slight inaccuracies in location of the work. The pilots are bullet nosed or acorn shaped, and for a short distance, equal to the metal thickness or less, are straight, to fit closely the previously punched hole used for location. Where the pilot is placed in the face of a blanking punch there is a tendency for the blank to stick on the pilot and go up with the punch. This is opposed by the natural tendency of the blank to stick in the die, but clearly such a pilot must not fit the hole as tightly as is possible when the pilot is independent of the blanking punch and can have a stripper to shed the metal, as in progressive operations on strip material.

Before proceeding to the discussion of the specific types of dies belonging to the shearing group, we may note several possible arrangements of die steels. In Fig. 33 the die steel is all in one piece screwed on top of a simple base plate, from the back. In Fig. 34 the die steel is in one piece but is set into an accurate counter-bore in the die base, being thereby located correctly with respect to the punch. Every device to assist in obtaining accurate location and close workmanship is of importance when the metal is thin. In Fig. 36, the die steels are in many short sections fitted together and screwed into stiffly ribbed, cast-iron holders to prevent deflection under the back thrust in operation. A composite steel made up of tool-steel facings welded onto lower-carbon backing pieces are used on many large dies of this sort for economy. Smaller dies also are often built up out of small sections to minimize troubles from distortion in hardening the common die steels and to permit replacement of single sections which may become broken or chipped without replacing the whole die. For odd-shaped blanks, machining is often easier if the die steels are made in sections.

CHAPTER IV

THE SHEARING GROUP OF PRESS OPERATIONS

The operations which belong in the shearing group have been arranged in a somewhat arbitrary sequence as follows: blanking (including multiple blanking and progressive blanking), piercing and perforating, compound blanking and piercing, follow-die piercing and blanking, blanking and repunching, shearing, parting, notching, slitting, trimming, shaving, broaching, hot punching, the combination of shearing operations with other types of operations, and the use of hollow cutters and adjustable dies.

Blanking.—Blanking is the cutting of shapes or blanks out of sheet metal. The die or female member is made to size, where exact size is important, and the clearance is taken off from the size of the punch. The face of the punch is ground flat, in order not to distort the blank, and any shear is ground on the die. Where the blank is very large compared to the metal thickness, warp or curvature in the sheet may result in measurable inaccuracy of shape even though the die is accurate and the punch is flat.

The fact that the blank follows the shape of the punch, whether flat or otherwise, is used when it is desired to form the blank into any shallow shape while blanking it. Forming or plastic cold-working of metal takes place between its elastic limit and its ultimate strength. Shearing is essentially tensile failure at the ultimate strength. Consequently, if the face of the blanking punch has any convex contour, the metal will be stretched plastically to that shape before shearing occurs. Provision must sometimes be made for holding the sheet while forming in blanking. This subject will be discussed again with the drawing group of operations.

Large pieces awkward to handle, such as the running-board guard, Fig. 36, are usually blanked singly from sheet material sheared into blanks of about the right size in a squaring shear. Many blanks, also, are produced from scrap left from the production of other parts and necessarily require separate handling. Such dies require only to be simple and free from obstruction, the gauging being done either by eye or with gauge pieces at the back of the die.

Fig. 41 is an example of progressive blanking, or cutting one piece

out after another in rapid succession, from strip or coil material. After each stroke of the press the strip is advanced a distance equal to the width of the blank in the direction of feeding, plus an allowance for the desired scrap between blanks. This scrap allowance varies from nothing, where a little variation in the outline and cross-section profile of the edge is permissible, to an amount not less than the metal thickness where the edge profile must be kept as square as possible, or to an amount slightly greater than the maximum variation or error in the length of advance in the case of mechanical feeding.

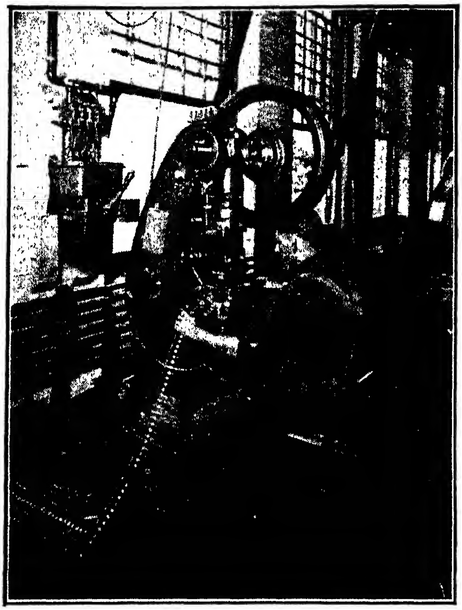


Fig. 41. — Hand-fed progressive blanking, catching every stroke of the press.

The press in Fig. 41 is kept running continuously, or practically so; and in order to govern the distance the strip is advanced each stroke, an automatic finger gauge is provided on the press. As shown in Fig. 42 *A*, the finger drops through the last hole blanked in the strip at a point close to edge of the die. A cam on the press shaft raises and drops the finger after the blanking of each piece. Thus the operator has only to maintain a tension on the strip and achieves practically automatic feeding as the finger releases and catches the strip.

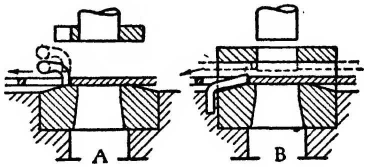


Fig. 42.—For locating the strip in progressive blanking, the cam-lifted finger gauge (cut *A*), or the fixed gauge with metal clearance above it under a fixed stripper (cut *B*).

A variation on this method is obtained by placing a fixed gauge pin at the side of the die in a location similar to that of the finger gauge, as shown in Fig. 42 *B*. The pin extends above the die surface an amount slightly greater than the metal thickness. A fixed stripper is provided at such a height that the metal will clear the top of the stop pin in being stripped off the punch. The operator maintains a tension on the strip

to the side and down so that at each stroke the band of scrap slides over the gauge pin while the solid metal stops against it. Occasionally the pin is set right up to the cutting edge and the thin scrap is broken instead of being lifted over the stop pin.

In mechanical feeding no such stop gauge is necessary, as the ordinary roll feed advances the strip the desired amount between strokes. This should be qualified, however, as some continuously revolving type roll feeds, with roll relief, do use the finger gauge and imitate manual operation.

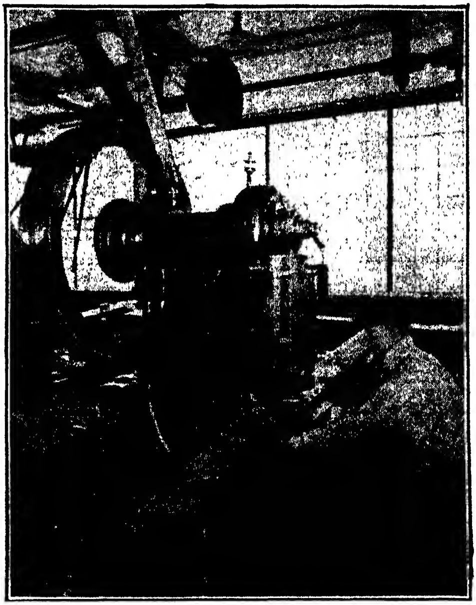


Fig. 43.—Progressive blanking down one side and back the other side of a strip for metal economy with odd shapes.

A modification of plain progressive blanking, for the sake of economy of material, is illustrated in Fig. 43. In order to leave a minimum of scrap the strip is fed across the die once as shown, then flipped over and fed back in the opposite direction cutting blanks out of the scrap. The same scheme may be developed, as shown at *B* in Fig. 44, by using a double die, the punches being placed so that one punches the shape, turned around, out of the scrap left by the other. It has been found that where the exact profile of an irregular shape is of extreme importance (as for accurate relocating), the double dies are difficult to make and maintain as exact duplicates. It is practically impossible to do so, where the dies have straight walls only part way down, and are ground down eventually below this straight portion. Such dies have been successful, however, with straight walls all the way down, and the blanks not

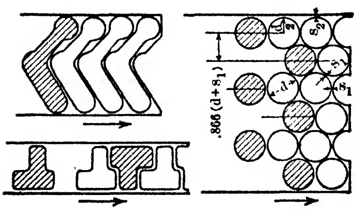


Fig. 44.—Economy of material in progressive blanking with a single die (*A*), a double die (*B*), and multiple blanking (*C*).

pushed through but returned to the scrap and carried out with it.

The best economy of material can be obtained, for some shapes, only by arranging the blanks at an angle, as shown at *A* in Fig. 44. Other shapes will give the best economy only with a double die, or by running through twice, which gives the same result. Rounds and similar shapes give the best economy by staggering or interlocking the blanks in lines as indicated at *C* in Fig. 44.

A die for the multiple progressive blanking of round discs for extrusion, based upon the staggered arrangement (*C*) for maximum scrap

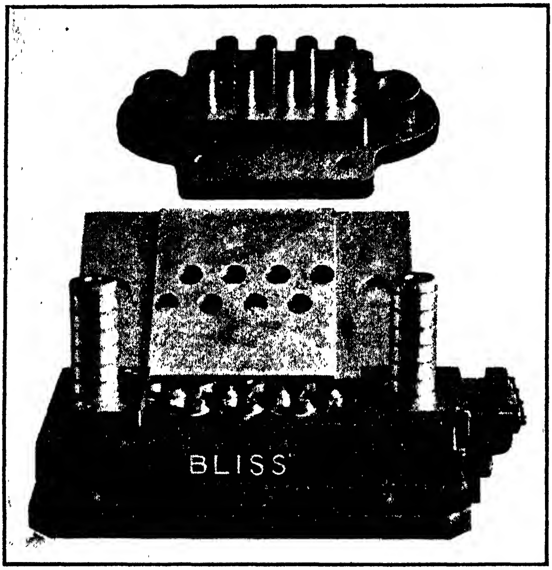


FIG. 45.—A progressive multiple blanking die. For round blanks the material saving is large as compared with single-row strips.

economy, is shown in Fig. 45. Similar methods are used for the production of round blanks for electric motor laminations. These are cut five or six per stroke from full-width sheets with a saving in material of 8 to 15 per cent over the earlier method of progressive blanking from single-width strips, and saving of the slitting operation. The die shown in Fig. 45 is built with separate bushings or rings set into the holder for each blank. This lowers maintenance cost and hardening loss due to possible breakage or distortion. The strip metal is guided between a fixed guide on the left and a spring guide on the right so that variations in width of strip may be taken care of with a minimum allowance of

scrap at the sides. The stripper plate rides on the same substantial guide pins used for the punch plate and is actuated by cams on the press crankshaft to hold the strip quite tightly during blanking.

It should be noted, at *B* and *C* in Fig. 44, that the punches are not located in the closest possible adjacent spaces. To do so would make the dies too weak or the scrap allowance too great. Accordingly they are spaced apart as indicated, permitting in many cases the use of separate steels for each die. The problems of metal economy and die strength make multiple blanking without the progressive feature generally impracticable.

Dies have been made for cutting a number of blanks out of a full sheet of tin-plate each stroke, but the dies were expensive and rather weak, and the scrap loss was unduly high. The best economy of material in cutting round blanks from sheets of tin-plate has been obtained by the use of a single die in a press arranged for stagger feeding and progressive scrap cutting.

In large-quantity production with automatic feeds, plain blanking operations permit shorter press strokes than almost any other shearing operation and consequently permit higher operating speeds with economic tool life. This is providing the tools are accurately made and the press is amply stiff, of course.

Hole Cutting, Piercing, Perforating.—In hole-cutting operations the metal punched out is the scrap. Consequently any shear must be on the punches, and the die must be flat in order not to distort the work. Shear on the individual punch is of little value unless the punch is large compared to the metal thickness, as in Fig. 46. Therefore shear, in the case of small punches, is usually obtained by stepping the punches, as in Fig. 49. This is of importance also when the punches are close together relative to the metal thickness to minimize the shifting of delicate punches due to crowding in the metal caused by adjacent punches. The die clearance for small punches should be relatively large, to reduce the stripping load. If the punch need enter only a quarter of the metal thickness, for example, to effect shearing, then each punch need be shorter than the next by no more than this, as illustrated in Fig. 49. If the punches are stepped more than the amount necessary to effect shearing and the clearance is ample, their progress through the metal will be a jerky series of loads and releases. It has been mentioned that, in punching small holes close to a large hole, especially in thick metal, the small punches should be ground shorter than the large punch to prevent deflection and chipping due to crowding.

For ordinary purposes, holes smaller in diameter than the thickness of the metal should be avoided. Even then, careful polishing, a good

fillet under the flange, no sharp change in section and good guiding are essential to the life of the punches. A good deal of breakage on fine punches seems to occur or appear in stripping. The severity of both punching and stripping loads is reduced by increasing the clearance between punch and die to as much as a quarter of the metal thickness all around, on mild steel.

When the diameter of the hole is important, its dimension becomes

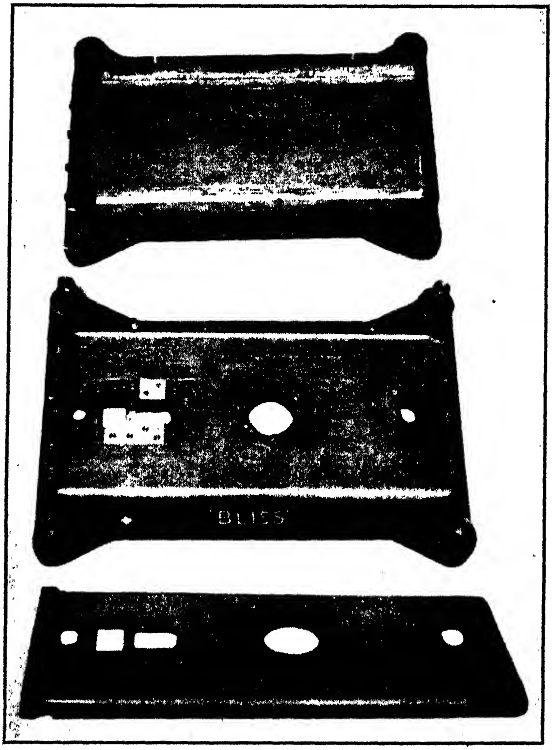


FIG. 46.—A hole-cutting die in which the die-base serves to locate the stamping.

the punch diameter and the die is larger by twice the amount of the clearance. The reason for this is apparent in Fig. 21.

Most separate hole-cutting and piercing operations are of a secondary nature. That is, they are performed on articles previously blanked or blanked and formed. Usually this is because holes pierced at the time of blanking would be distorted in the forming operation or would not come uniformly in the right place. Accordingly, provision must be made for locating or gauging the work. Thus, in Fig. 46, most of the

die base is a form over which the jacket fits for location. It is held down solidly in place by a spring-actuated stripper with wooden contact strips on the edges. The stripper is mounted on the punch plate. The die is made up of sectional steels screwed and doweled in place and shimmed up for regrinding to maintain the proper level. Four substantial guide pins are used and are close fitting, as the metal is comparatively thin.

It is possible in piercing dies to arrange to punch simultaneously at different levels providing the formed parts are uniform in dimensions. This was done, for example, in perforating flange holes around the top, and a drain hole in the bottom of an automobile crankcase. A long-stroke press was clearly necessary.

Some formed or drawn parts in which holes must be punched are of such shape that horn dies must be used. The horn may be a small and delicate affair, like that shown in Fig. 47, arranged for mounting on the press bolster, or it may be a large and substantial forging or casting mounted on the face of a suitable horning press. In the latter case the die is merely a tool-steel plate screwed and doweled on top of the horn. The more sustantial the horn, the better it is for the life of the die. In Fig. 47 the whole horn is the die and acts as a stripper too, as the shell to be pierced fits over it quite closely. We have seen horns as small as a ¼-in. diameter used in piercing the walls of small shells or tubes.

In some cases the horns stick up vertically from the bolster plate, and punches, acting in a horizontal plane, to pierce the sides of drawn shells, are operated by means of wedge mechanisms from the press slide.

Perforating is the punching of many identical holes in the sheet, blank or previously formed article.

The simplest or crudest manner of perforating is by the use of a single punch under which the sheet is moved to a proper position for each hole. One method of doing the locating is to lay out the positions of the holes on the sheet, marking their centers with a prick punch. A boiler punch with a conical point in the center of its face for location is used in the press, and the plate is moved about so that the point corresponds with each prick-punch mark in turn. Where the plate is heavy it may be supported on a two-way movable carriage.

Another method of location for small-quantity production is to use a master plate with holes properly punched and crescent or semicircular gauges riveted at each hole. The master is clamped to the plate to be punched and is moved about, the crescent gauges being brought tight against the punch or punch holder for each location.

In some cases the punch holders are arranged so that the punches can move vertically freely, each stroke of the press, without cutting. A gag is provided to slide back of the punch by hand and cause it to operate when desired. Such a scheme is employed with several punches of different diameters side by side in a common holder. These are used to pierce single holes of whichever diameter is desired, in structural iron work, etc.

Fig. 48, showing a shaker top die, is a good example of multiple

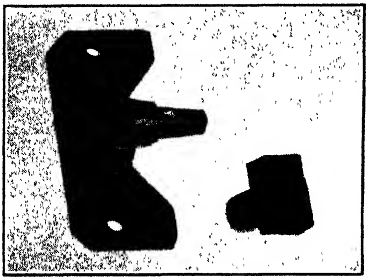


Fig. 47.—A horn die for a piercing operation.

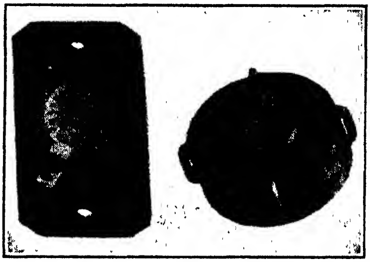


Fig. 48.—A perforating or multiple piercing die for a shaker top.

perforating. There are many operations in which all holes are pierced together in a single press stroke, the essential considerations being accurate relative location of holes in the punch holder, stripper and die after hardening the die, and usually a good fit in the stripper to support the delicate punches.

Most multiple perforating however, is done progressively with mechanical feeds. Fig. 39, in the preceding chapter, showed a die arranged for perforating up to forty-two $\frac{3}{8}$-in. square holes each stroke of the press, a feed being arranged to advance the sheet for any number of rows of holes up to about forty per sheet. To change the number of holes per row, more or less punches were left out. All the punches were ground to the same length but arranged in the holders to give a stepped effect for shear in line with Fig. 49. Some of the feeds for progressive multiple perforating shift the sheet right and left as they advance it, to give a staggered effect to the perforations. Others gag alternate punches, all the way across, in or out simultaneously for the same effect.

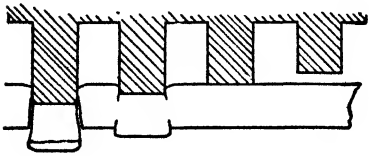


Fig. 49.—Perforating punches stepped sufficiently to avoid crowding.

Indexing feeds, for cylindrical or conical shapes or flat discs, rotate

the blank the proper number of advances, piercing one, two or more holes per stroke of the press. The details of such feeds are important but will not be discussed here. All such equipments have the common characteristics of clamping the blank centrally, accomplishing a predetermined number of strokes and stopping. Conical and cylindrical lamp burner-shells, conical colanders, circular ornamental plates and the larger motor laminations all come in this category.

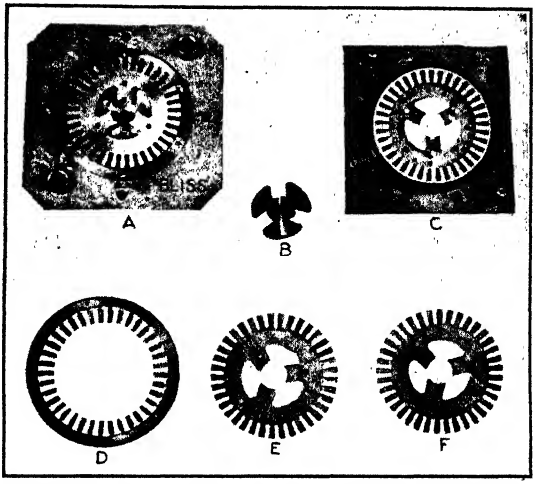


Fig. 50.—A compound die for a motor lamination, disassembled.

Compound Blanking and Punching.—Compound dies which blank out a shape and pierce the holes in it simultaneously afford the most accurate method of obtaining pierced blanks, though not the fastest.

The compound die is regularly an inverted type. The blanking punch, made to include the piercing dies, is on the bottom so that the scrap punched out of the holes will be pushed through and fall out under the bed of the press. The blanking die, having the piercing punches mounted in its holder, is on top, mounted on the slide of the press.

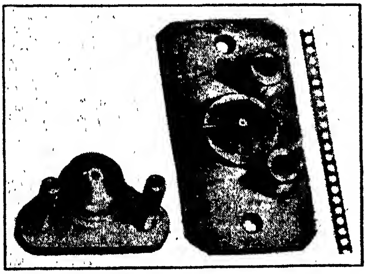


Fig. 51.—A compound die for blanking and piercing a small gear.

The sheet scrap is usually lifted off the punch (bottom) by means of a spring stripper, the springs being either under the bed of the press with pins up through the bolster as in Fig. 50, or in punch base itself as in Fig. 51.

The blank tends to stick in the die and go up with it. Accordingly, spring strippers may be provided to deposit the blank in the scrap if the metal is fairly thick relative to the size of the blank, or on top of scrap if it is relatively thin and tends to warp, in either of which cases

the blank and sheet scrap are removed together. Or the blank may be allowed to stick in the die until the slide approaches top stroke, when it is stripped out by means of the cross-bar knock-out in the slide. In this case the press is usually operated inclined to the rear so that the blank will fall back more or less clear of the die, while the sheet and its scrap are moved across the surface of the die. If the blank does not fall back fast enough, an air jet, or in some cases a spring trigger, may be used to snap it back.

The compound die shown in Fig. 50, producing the rotor lamination *E*, is disassembled to show the component parts. The cutting steel of the part *A* acts as blanking punch and also as die for the center opening and the three small round holes. The sheet scrap is lifted off this blanking punch by the close-fitting ring *D*, actuated by springs under the press-bed. The center scrap instead of being pushed through, as is more usual, is returned to the surface by the stripper plate *B*, also actuated by the springs under the press. The top plate *C* carries the blanking die, the center punch and the three hole punches. The blank is stripped out of it by the spring stripper plate *F*.

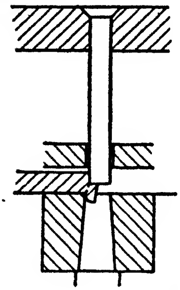


Fig. 52.—In cutting part blanks, delicate punches deflect and chip or wear against the die edges.

The running board die shown in Fig. 36 is of the compound type and pierces nine small holes as it blanks. The die shown in Fig. 51 blanks a small gear, punches the center hole absolutely concentrically in it and returns the gear to the scrap to be carried out.

Shear may be applied to blanking *dies* and piercing *punches*. Clearance allowance may be taken off the sizes of blanking *punches* and piercing *dies*. In both cases the comments are the same as apply to simple blanking or piercing tools, but the function of the particular part must be kept in mind. In the case of the lamination die, Fig. 50, the metal is so thin and hard (0.014 in. silicon steel) that the difficulty is to keep the clearance small enough (under 0.001 in.) and the pilots close fitting enough to keep this clearance centralized.

It is extemely important, in both this and the following type of dies, to prevent cutting "half blanks." This is liable to occur in blanking from strip material, if care is not taken to avoid it at the ends of the strips. Thus as illustrated in Fig. 52, if a delicate punch strikes midway on the edge of a strip, there is a decided side thrust which bends the punch, destroying its proper clearance and causing it to strike against the die edge, either chipping or wearing materially. Fig. 52 is somewhat exaggerated for emphasis, but it has often been

demonstrated that the cutting of occasional part blanks with fine punches lowers the life of the die to as much as a third or a quarter of what might properly be expected of it.

Follow-Die Piercing and Blanking.—The principal alternative method of producing pierced blanks is to use what is known as the follow-die, Figs. 40 and 54. As shown in Fig. 53, the holes are pierced first and then the strip is advanced to a proper location under a blanking punch and the blank is cut out.

As both the hole scrap and the blank are pushed through the die, the press strokes are shorter and the operating speeds are usually materially higher than in the case of compound dies which must dispose of the blank above the die surface. But as the blanking and the piercing are done separately, mechanical means of getting the proper location must be employed, and in this there is room for error which does not enter in the case of the compound die which blanks and pierces each blank simultaneously.

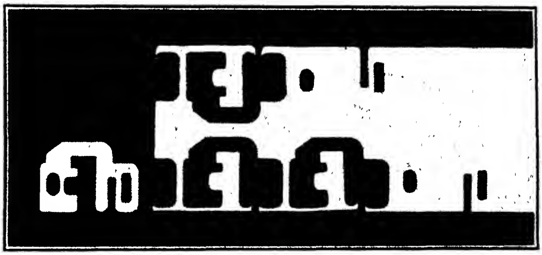


FIG. 53.—Progressively pierced and blanked in a double follow die.

When follow-dies are used, the strip may be fed by hand, using a finger gauge or stop pin as described in connection with Figs. 42 *A* and *B* to stop it with the pierced hole in about the right position relative to the blanking punches. It is becoming more and more common, however, to use mechanical feeds which advance the metal approximately the correct amount between the piercing and blanking stations. In either case there is likely to be some inaccuracy in the location of the pierced holes in the blank, to correct which pilots are used.

As illustrated in Fig. 54, these pilots are placed in the face of the blanking punch (54 *B*) or in an intermediate position between the piercing and blanking stations (54 *A*). The pilot may be bullet nosed, acorn shaped or like the frustum of a cone. It enters the previously pierced hole and shifts the strip to the correct location. Consequently there must be sufficient taper on the sides of the pilot to compensate for the greatest possible error in location. Also there should be a straight portion on the pilot for the final location equal in length to say half the metal thickness, or more if the metal is hard or scaly so that it subjects the pilot to considerable wear.

Placing the pilot in the face of the blanking punch, Fig. 54 *B*, is the commonest practice, but necessitates the pilot being a loose enough fit in the pierced hole so that the blank will stick in the die and not on the punch. By using an intermediate position (Fig. 54 *A*), the pilot can be a closer and more accurate fit as it has the benefit of the stripper. In this method, however, the last blank on each strip goes unpiloted so that its greatest application is for coiled metal of considerable length.

Where sufficient scrap is left anywhere around the blank it may be utilized for pilots of the type shown in Fig. 54 *A*. In this case the advantages of separate pilots are available without the disadvantages of having to have an intermediate position for piloting. The pilot

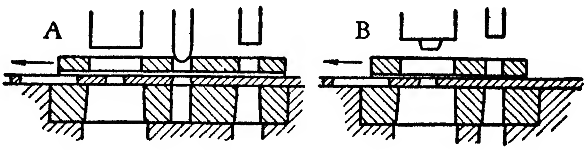


FIG. 54.—Follow dies for progressive piercing and blanking, with an independent pilot (*A*), or a pilot in the blanking punch (*B*), to correct the strip location.

holes are punched with the other holes at the piercing position, and the pilots are located beside the blanking punch at the blanking position.

In timing follow-die operations in mechanical feed presses, it is usual to allow the upper half of the stroke for feeding. Then at mid-stroke the nose of the pilot must clear the strip. Consequently (the lower) half of the press stroke equals the length of the pilot, plus a small allowance for clearance, plus the metal thickness, plus the amount the punch enters the die, which depends upon the shear or stepping of punches, and the spring of the press. The length of the press stroke is one of the principal factors in determining speed of operation. Accordingly, where high speed is desired, the pilots must be kept as short as is practicable.

It is possible to pierce and blank two or more pieces out of the same strip, in multiple follow-dies, as indicated in Fig. 53. It is also possible to perform three or four consecutive piercing and blanking operations in follow-dies. Then pilots may be used just at one station in the case of coiled material, or at the second and last stations in the case of 8- or 10-ft. strip material.

In hand feeding to a gauge, in order to have the first blanks pierced, it is necessary to provide manually controlled gauges to stop the strip in the correct positions on the first two or three advances, before it reaches the automatic gauge.

Blanking and Repunching.—One other method of producing pierced blanks is worthy of note. It is used largely on fairly complicated blanks, as illustrated in Fig. 55, where the die sections would be too delicate and the crowding too severe for a compound die, and where the accuracy required or the difference in direction of shearing is considered to be against a follow-die.

The outline is blanked in a simple blanking die, from strip material. The piece is then located in a gauge or nest, and the narrow slots and holes are punched in a simple piercing die relieving the delicate punches of considerable strain and separating them in upkeep from the huskier

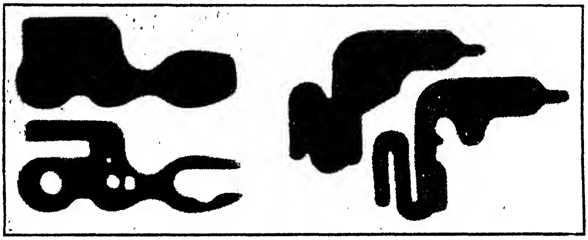


FIG. 55.—Blanked progressively, then located to gauge for piercing.

blanking die. In some cases where the small holes are very close, two repunching operations are employed.

Shearing, Parting, Notching.—The characteristics of these three classes of operations, as distinguished from those just discussed, are principally in the matter of balance and the results of the side thrust due to the compressive stresses in the metal. Shearing is cutting on a single line, usually a straight line. Parting is cutting simultaneously along two parallel lines or at least two lines which balance each other in the matter of side thrust. Notching is really blanking, unbalanced, in that it is cutting around only three sides (usually) of a punch.

It will be noted in shearing that secondary shearing and jagged fractures, Figs. 21 and 23, are ordinarily absent. This is because the metal is free to move away from the cutting edges in both directions and the fractures meet.

Fig. 56 *A* illustrates the natural tendency of a free piece of metal to tip as it is being pinched between two shear blades. At the resultant angle the compressive stresses balance on the two faces of each shear blade, during the plastic deformation period between exceeding the elastic limit and fracturing. See also Fig. 26, showing the stresses in blanking.

In squaring shears, however, one part of the metal is held down flat by the clamping bar. The other part, as shown in Fig. 56 *B*, bends down to equalize the compressive stresses on the under face of the moving blade and the side face of the fixed (lower) blade. Instead of being square, the under side of the moving blade is sometimes finished at an angle as illustrated. This shape is described as "rake" and reduces the bending by a small amount (equal to perhaps half the angle). Blades which do not have rake are ground square and may be reversed giving four cutting edges before they have to be reground.

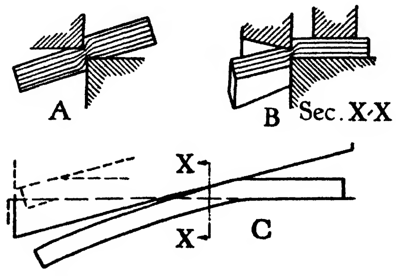


FIG. 56.—Distortion in shearing; unrestrained (*A*), with one hold-down and rake on one blade (*B*), and due to angle of shear of upper blade (*C*).

One blade of a squaring shear is regularly set at an angle with the other, Fig. 56 *C*. This reduces the working pressure as discussed in connection with Figs. 28 and 29 *a* but causes a progressive bending which is exaggerated for illustration. If a long narrow strip is sheared from the edge of a relatively thick piece of sheet metal it receives a considerable permanent twist. The twist is the result of the two bending actions, Fig. 56 *B* and *C*. A similar distortion is present in the edge of every sheet sheared off in a squaring shear, though it is less apparent in wider sheets because the straining occurs just at the edge.

A shearing die has the same characteristics as a squaring shear, and if the blades must be at an angle the edge of the blank will be somewhat distorted. If the load is not too great the blades may be parallel (without shear), as in Fig. 57. In some cases, too, spring plates may be provided opposite both upper and lower blades to prevent the bending (56 *B*).

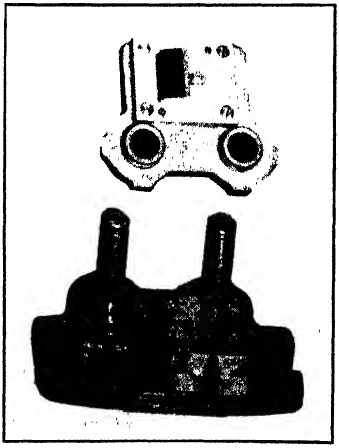


FIG. 57.—Progressive piercing and shearing off, advancing by hand to a stop.

Where the load is large, the blank may be separated from the strip by parting out a narrow strip of scrap about as shown in Fig. 58 *E*. The punch is a narrow blade shearing on both edges and may have any

angle of shear as it distorts only the scrap piece. Parting dies are quite widely used in producing articles from narrow band strip, and to some extent for wider sheet. Such dies, as indicated at *D* and *E*, Fig. 58, usually serve the double purpose of separating and notching or outlining the end of the strip or blank.

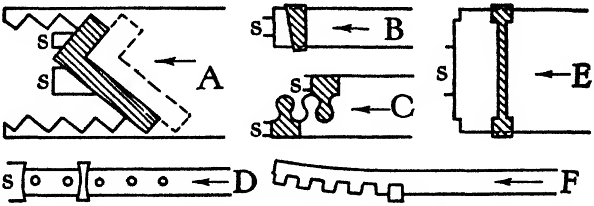


Fig. 58.—Shearing (*A*), shearing and notching (*B*), double shearing (*C*), piercing and parting (*D*), parting and notching (*E*), notching (*F*)—all being progressive operations.

In both shearing and parting dies the length of the piece to be produced is usually determined by feeding to a stop (*S*). Piercing operations can be combined with either shearing or parting as illustrated in Figs. 57 and 59. To have the piercing punches stepped shorter than the parting or shearing punches by an amount not less than the penetration to effect shearing, is even more important in these cases than in follow-dies as the side thrust in the metal is unrestrained by any scrap.

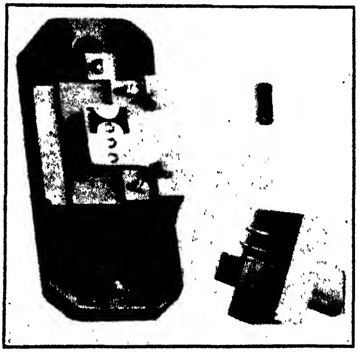


Fig. 59.—A progressive piercing and parting die.

The effect of the crowding action in the metal is apparent again in progressive notching. Note at *F* in Fig. 58 that in notching one side of a narrow strip the metal on that side is spread and a considerable curvature results. The same effect is apparent in blanking down one side of a strip, reversing it and blanking down the other side, as in Fig. 43. The strip is bowed very materially, its length being increased along the side where the first row of blanks is cut, and the condition is corrected when the second row is blanked.

Fig. 58 *A* represents an application of progressive shearing. The metal is fed continuously against the stops (*S*) and the descending punch cuts principally along its right-hand edges. This unbalanced shearing creates a considerable side thrust tending to move the punch to the left

and the die to the right. To overcome this tendency it is good practice to provide substantial pilots as in Fig. 57, or to make the stops (*SS* in Fig. 58 *A*) extremely substantial and finished off, so that they can serve as a backing for the punch.

A double shearing die for producing two blanks of simple shape, each stroke of the press, is shown at *B*, Fig. 58. One blank is pushed through the die and the other slides off the top. The die for producing two spoon blanks per stroke, as shown at *C*, combines notching and shearing and is a little more elaborate though somewhat similar.

Slitting.—Slitting operations though often along single lines, are usually more akin to blanking than to shearing and have some features

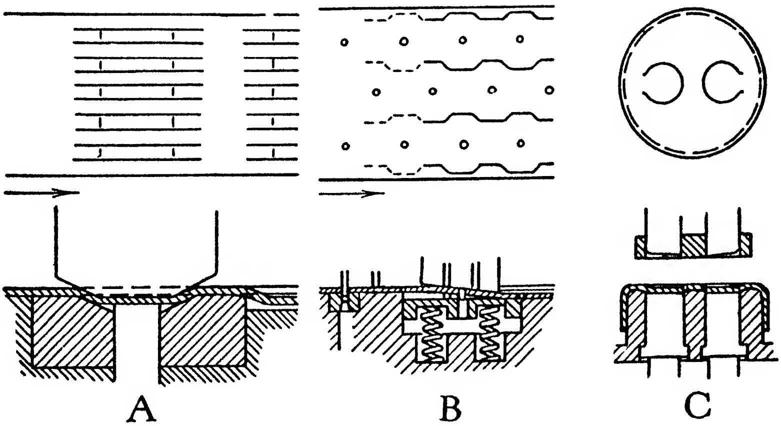


FIG. 60.—Three types of slitting operations with different characteristics.

all their own. Clearance, depth of penetration, lost motion in the press and spring of the press are of extreme importance.

Fig. 60 shows plans and section elevations of three types of slitting operations. At *A* is illustrated slitting to fracture for a desired length, neither more nor less, as in one method of producing metal lath. Progressive slitting of scroll strips is illustrated at *B*. And the slitting of knock-outs for electrical conduit boxes, shaker-top cans, etc., is illustrated at *C*.

Most presses spring or stretch somewhat because the materials of which they are made are elastic (which is fortunate). The gap or *C* frame presses spring considerably because the center of gravity of their frame sections is always quite a distance back from their working center lines. But note that as the load builds up in a shearing operation the press stretches proportionately until the point of fracture of the blank is reached. Then if there is no shear on the dies and if there is ample

clearance, the fracture is sudden, releasing the load and allowing the press to snap back to normal and beyond. That is why it is often necessary to set the punch to enter the die an appreciable distance under no load conditions to effect shearing at all.

Clearly a springy press would not give uniform results on operation 60 *A*. As rigid a machine as possible should be selected, and even then it is likely to be desirable to provide contact faces in or beside the die to insure consistency in the depth of entry regardless of variations in lubricating films, or in thickness and hardness of material, etc. In using such contact faces, it is necessary to use care in setting dies and it is usually necessary to provide a press of somewhat greater capacity than would otherwise be required.

Progressive slitting, Fig. 60 *B*, is like progressive shearing in a squaring shear. The upper blades are at a considerable angle of shear and do not quite enter the metal at the end of the stroke on the high end of the blade or punch. The blades are longer than the distance advanced each stroke, so that there is an overlap, and each new cut is started from the end of the last cut. A rigid machine is desirable, but spring is not so important as in the last case because there is no sudden shock or release. It is desirable to pilot the metal in progressive slitting, so that each new cut will line up exactly with the end of the last cut and not leave a sliver.

In slitting knock-out tabs, Fig. 60 *C*, the conditions are very similar to those in case *A*, especially if the punches are flat. The hit-home principle will prevent over-travel but requires careful die-setting in order not to strain the press. If considerable shear is used on the punches, the load is easier and more gradual, but it is still important to prevent over-travel due to variations in metal or temperature, etc. In this case also the tabs are more seriously distorted and not so easy to push back tightly into place, a job usually done by springs of suitable capacity.

In any case, if there is sufficient clearance for a clean fracture and the die-set is closely piloted so that the clearance will remain equally spaced, there will be no ragged secondary shearing (to prevent the tabs going back properly), and it is not necessary to penetrate so far to obtain the fracture. On thick material, tapered punches are sometimes used to open up the hole so that the tab may be pushed back absolutely flush.

Trimming.—The trimming of previously drawn or formed or forged parts, etc., is closely related to either blanking or shearing, and is necessarily a secondary operation requiring the separate handling of each piece whether by hand or mechanically.

When shells, shallow or deep, are drawn with a flange, the outline of the flange is always more or less irregular on account of the drawing. To trim such flanges to a regular outline the die is quite similar to a blanking die, though with some provision for locating the shell. Thus in Fig. 61 the motor oil pan is dropped into the shape formed by the inside of the die steels (at the right). The trimming is done on the outside edge of these steels. Two wedge-shaped or knife-edged scrap cutters are set into the holder on the long sides. The scrap, as it is trimmed off, is pinched between these scrap cutters and the face of the punch steels, separating it into two pieces so that it is easy to remove.

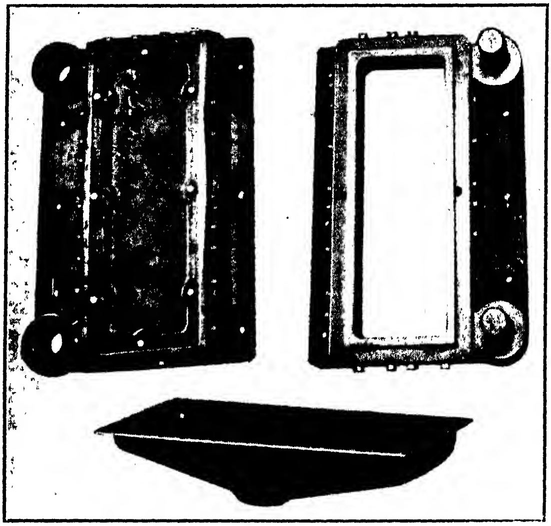


Fig. 61.—Automobile oil pan trimming die with wedge scrap cutters.

The punch plate, at the left, has eight spring pins set into its face to strip the pan out of its steels.

In some cases, shells are drawn with a narrow flange and it is desired to trim off all the flange by pushing the shell through an ordinary blanking die, as illustrated in Fig. 62. The trimmed flanges may be stripped off the punch with an ordinary spring stripper, or allowed to accumulate and to break up against wedge scrap-cutters as shown. The cross-section appearance of edges trimmed in this manner is indicated at *B*. In an effort to correct this, such shells are sometimes pushed through an ironing die, but the results (62 *C*) are usually not especially satisfactory.

To trim the edges of straight-walled shells square, whether they originally had a flange or not, there are several methods.

The simplest from the die standpoint, and the slowest, is to put the shell over a horn die and shear down on the edge, turning the shell say four times to complete the operation. It is almost impossible, however, to make such cuts join up exactly. Notching operations may, of course, be combined with the trimming on such horn dies.

There are two methods of trimming drawn shells (usually flangeless) in dies, which give square edges and a continuous cut without joint marks. Both are based upon setting the shell into a flat die which fits it at the trimming level, then bringing another die down inside the shell to the same trimming level, and imparting a sidewise motion to one of the dies in several directions from the neutral center to shear off the scrap all around. The principles are illustrated in Fig. 63. Note that there is usually a floating filler piece inside the shell being trimmed, to control the trimming level closely. Note also the pins around the inner (upper) trimming die to maintain the exact relative shearing level of the inner and outer dies. These pins are ground with the surface of the inner die, and slide upon the flat-ground top surface of the outer die.

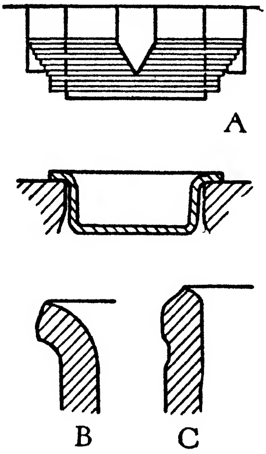


FIG. 62.—A trimming die with scrap cutters (A), the edge as trimmed (B), and as ironed after trimming (C).

Fig. 64 illustrates one method, the patented Brehm trimming die, having three wedges at 120° to each other, and a spring-mounted outer die with corresponding wedges at suitable levels. The shell is dropped into place and the press slide descends, centering the inner die and then

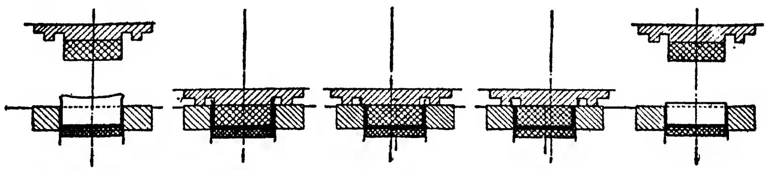


FIG. 63.—The shearing action of the dies shown in Figs. 64 and 65 which give a smooth square edge.

carrying the outer die down so that its wedges impart to it, in succession, sliding motions in three directions to effect shearing all the way around.

The other method is to use the Flat Edge Trimmer, Fig. 65, which acts upon the same principles as illustrated in Fig. 63, except that the

inner die is held down at the shearing level by long dwell cams and a four-directional shearing movement is imparted to the outer die

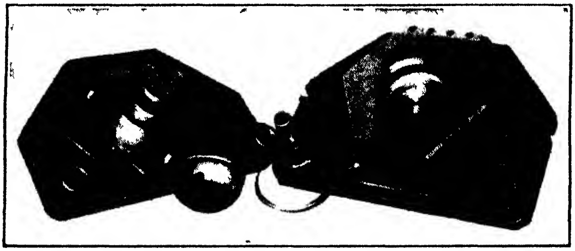


Fig 64.—The Brehm patented wedge action trimming die.

automatically by mechanism built into the bed of the machine. This makes the dies very simple by comparison. These dies are often

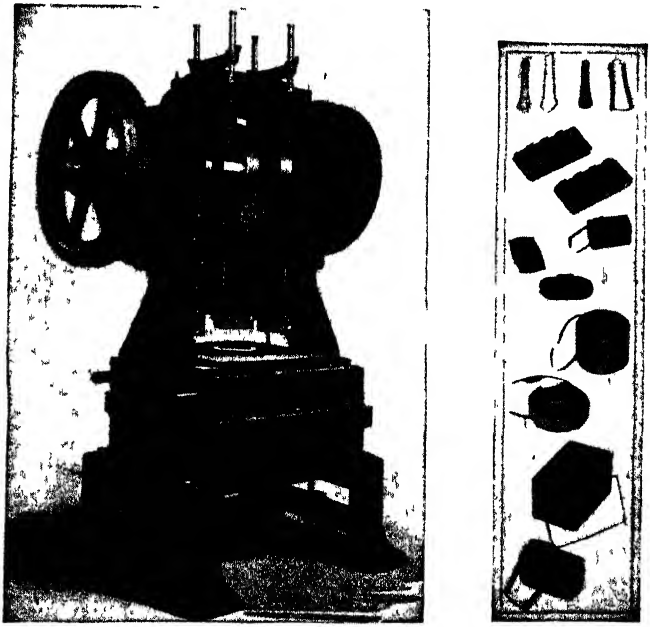


Fig. 65.—Shear action dies in the "Flat Edge Trimmer" may combine notching or hinge cutting with trimming.

arranged for cutting slots, notches, tabs, and hinge lugs at the same time that they trim the rest of the edge.

For plain circular trimming of drawn shells there are alternative

methods employing machines other than presses. Thus flanged shells may be trimmed in spinning lathes, Fig. 66, with cutters such as those illustrated in Fig. 113. This is usually done in connection with curling or wiring operations, and the direction of trimming must be watched in order to favor curling, which will be discussed in Chapter VI.

Straight-walled shells may be trimmed in a lathe with a regular parting tool, which is likely to be comparatively slow. Or they may be trimmed in revolving spindle machines with a circular cutter which is moved in to shear against a corresponding cutting edge on the chuck inside the shell. This is usually done in connection with curling, thread rolling, beading or similar operations.

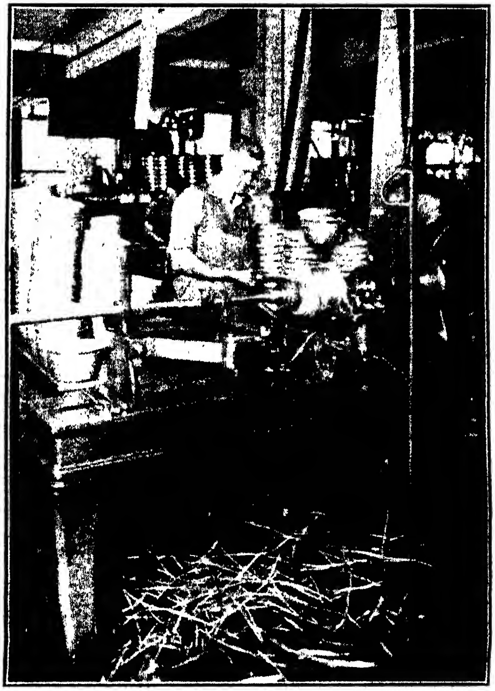


FIG. 66.—Spinning lathes may be equipped to trim and curl the flanges of round or oval shells and possibly burnish the bodies at one set-up. See also Fig. 113.

Returning to dies for trimming, the principle of wedge operation is often applied to making simultaneous horizontal cuts. Thus, in Fig. 67, the two sides of a casket end are trimmed by shear blades moved in by wedge surface at each side and returned by springs in the die base. The fixed shear blades are attached to the under side of the form which locates the stamping. A spring pad on the punch plate holds the stamping down. Instead of being made as shown, the wedges attached to the punch plate often take the form of large pins which first enter the die plate as guide pins. Their inside surfaces are slabbed off to wedge shapes. The fact that they are entered before the wedge action starts, balances all back thrust in the die plate and prevents any tendency to shift.

The floating die is another ingenious method of trimming opposing edges simultaneously. The die shown in Fig. 68, for trimming both sides of a fender together, is an interesting illustration of the principles.

The pad over which the fender fits is carried on four substantial guide pins and floats above the die base on heavy springs. There are corresponding sets of sectional trimming steels in both the punch plate and the die base which shear against opposing steels on the top and bottom edges of the floating pad. Three spring pressure pieces each, on the punch plate and die base, hold the fender tight against the floating pad while the shearing takes place.

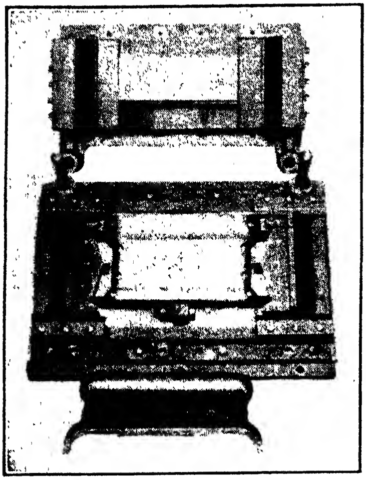


FIG. 67.—A wedge-action die for trimming both sides of a casket end simultaneously.

Trimming Forgings.—Forgings produced hot in presses or hammers are ordinarily produced with a "flash" or margin of excess metal which must be trimmed off. The trimming may be done by the hammer man or by a helper, while the forging is still hot, or it may be done separately after the forging has cooled. Small forgings are always trimmed cold because they will not hold the heat. Otherwise it is a question of quantity in production or shop methods and equipment. For the steady-production press-forging lines where the hot parts pass at a constant rate from one machine to the next, efficiency favors hot trimming, but otherwise in quantity production, it ordinarily favors cold trimming.

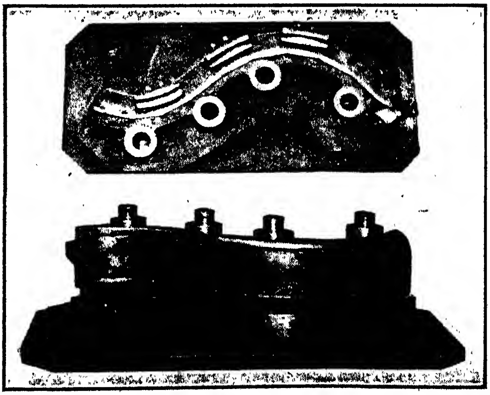


FIG. 68.—A floating die for simultaneously trimming both sides of an automobile fender.

In either case, the dies used are usually simple and rather crude looking. As illustrated in Fig. 69, they usually consist of more or less standardized holders with die steels bolted or clamped on top of them. The dies may be of the closed type, as shown at the right, which is common to cold trimming and some hot trimming. Or they may be open at the front, as shown

at the left, in order to trim the flash only and leave the end of the bar or the tong grip attached to the forging for handling purposes, if the forging is to be re-struck after trimming. In this case the holder is of the bridge type so that the forging may be pulled out to the front of the press. In this case, also, the tong grip must be sheared from the forging separately in the side shear of the trimming press, after the re-striking.

The dies are made flat without shear or rake and have a clearance angle in the hole of about 7°. For convenience in making and to take up wear, they are usually in two pieces as shown. The clearance between the punch and die is regularly around $\frac{1}{32}$ in. to $\frac{1}{16}$ in. on a side. The punch may be merely a flat pusher, as shown at the left in Fig. 69, if the forging is nearly straight walled (forging clearance only); or it may be shaped to fit the forging and support the flash to some extent, as at the right. The punches are dovetailed into the slide on most of the larger trimming presses, but can also be held in place by a punch stem, especially on the smaller gap frame presses often used for cold trimming.

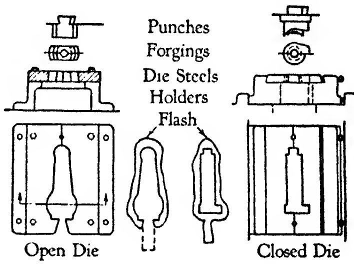


Fig. 69.—Typical open and closed dies for trimming the flash from drop forgings.

It is reported that "duraluminum" forgings cannot be trimmed cleanly in ordinary dies but require that the flash be pinched off between knife-edge blades.

Shaving and Broaching.—Shaving is trimming or squaring up sheared edges by removing a thin shaving of metal. Broaching is the same process applied to the finishing of more extensive surfaces, as the inside and outside of cast bushings, holes through forgings, etc.

These two press operations only, are closely related to the metal-cutting processes of machine tools. The rake and clearance of the cutting edges are or should be closely related to similar surfaces in the shapes of milling cutters, planing tools, etc. More often, however, especially for irregular shapes, die shaving edges are made square as in blanking dies, rather than sharp as in cutting tools, on account of difficulties in regrinding and holding to size.

Shaving operations are employed on the contact surfaces of blanked gears or cams, on straight knurled edges, fits or bearing surfaces (holes), etc. The sheared edge of the blank, before shaving, is rounded over at the top owing to the ductility of the material and is undercut or

ragged at the fracture, Fig. 21. It may be squared up roughly by shaving once, allowing for the shaving of 0.010-in. medium mild steel about a tenth of the metal thickness. The shaving allowance may be larger for thinner material and should be relatively less for thicker or softer material. For a more accurate job and especially for soft metal the piece may be shaved two, three or more times, removing less and less metal per shave. For extremely fine finish a round-edged burnishing die or punch, say 0.001 or 0.0015 in. tight, may be used. The finish which this gives is usually better than a machined surface. Table IV is taken from the standards of one large manufacturing concern whose practice is limited to one or two shaving operations on metals up to 5/16 in. thick. It is possible, of course, to shave materially heavier metal as well as extremely thin blanks.

Table IV

APPROXIMATE SHAVING ALLOWANCES

The amount of metal to be left on each edge of a blank or each wall of a hole to be shaved. Therefore double these figures for allowance on a diameter. (*Courtesy National Cash Register Co.*)

Thickness of Metal, Inch	If Shaving only Once, Inch	If Shaving Twice	
		First Shave, Inch	Second Shave, Inch
0.035 to 0.045	0.005	0.005	0.004
0.049 to 0.056	0.006	0.006	0.004
0.058 to 0.064	0.007	0.007	0.004
0.072 to 0.087	0.008	0.008	0.005
0.089 to 0.096	0.009	0.009	0.005
0.098 to 0.105	0.010	0.010	0.005
0.109 to 0.125	0.012	0.012	0.006
0.135 to 0.140	0.014	0.014	0.006
0.146	0.015	0.014	0.006
0.156	0.017	0.016	0.006
0.182	0.018	0.016	0.007
0.188	0.020	0.018	0.007
0.200	0.025	0.018	0.007
0.220	0.025	0.020	0.007
0.3125	0.025	0.022	0.007

Most shaving dies are made quite like blanking or piercing dies, though if both a hole and the periphery are to be shaved together, compound dies, Fig. 51, are the pattern. There should be little or no clearance between the punch and die and ordinarily no shear on either

the punch or the die. Accurate and close-fitting gauges or nests are required, one gauge (of three) pivoted in some cases to permit easy removal of scrap. Often the blank may be pushed through the die and the scrap carried up on the punch to be stripped off near top center where it can fall or be blown back. Similarly in shaving holes, the scrap may be pushed through and the blank raised on the punches to be stripped at top stroke and disposed of.

For shaving comparatively thick material one concern uses a vibrating type machine which it terms the jigger press. It has a special

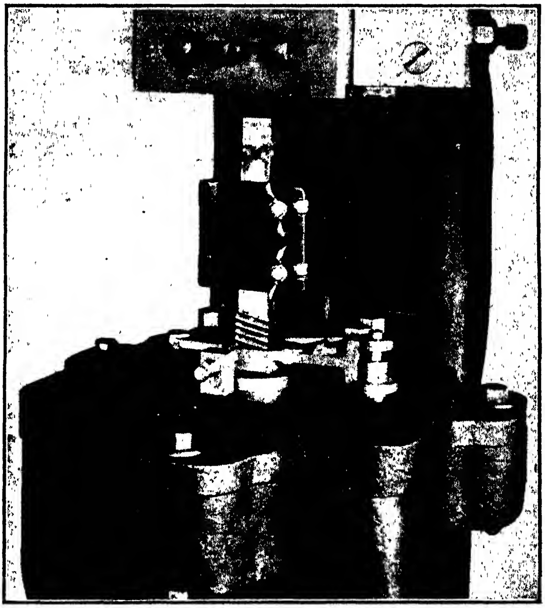


FIG. 70.—In broaching this cast-iron lever, the broach is pushed through, and returned by hand.

double cam drive which gives a rapid succession of short advances and dwells, and is claimed to eliminate an angular fracture and ragged edge at the end of the cut. This is difficult to account for theoretically, though the trouble may have been explained by a retarded down-travel or by previous use of too springy a press or too much clearance between the punch and die. It is important to use a stiff press, preferably of the straight-sided type, and close-fitting guide pins in the die shoes for shaving operations.

Broaching is really multiple shaving, taking off a number of cuts with the same punch or die by means of stepped cutting edges. These edges

are often shaped in profile, more like the flutes of reamers or milling cutters, than like blanking dies or punches. Broaching machine tools are pushed only one way through the work. Piercing punches are pushed through and pulled back through the metal. Broaching punches may be pushed through by the press and returned by hand as in Fig. 70, or pushed through and also pulled back through the work by the press as in Fig. 71. In the latter case, which is possibly limited to the softer metals, it seems necessary to protect the final cutting edges from over-

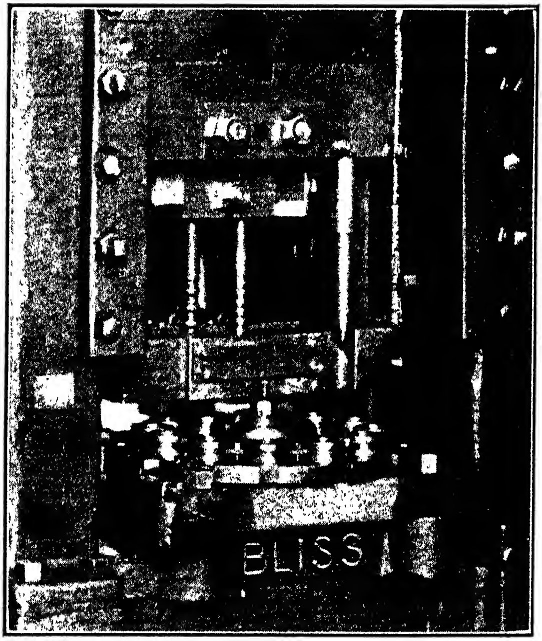


FIG. 71.—An automatic burnishing and broaching equipment in which the broaches are pulled back through the work. Crankpin velocity 47 ft. per min.

heating in drawing back by introducing a burnishing shoulder to enlarge the hole slightly. Also in broaching castings it is advisable to have a burnishing pilot on the end of the punch to centralize the punch and iron down small bumps on the cast surface.

Fig. 72 shows details of the two broaches used in Fig. 71 to rough burnish and then finish broach the hole through cylindrical castings, withdrawing the broaches through the castings. The slots in some of the cutting edges are to break up rings of scrap which might otherwise hold together on the punch.

For broaching or multiple shaving the outside surface of a shape, the

die is made up of a number of plates or dies piled on top of each other. The shape in each successive plate is smaller than that in the plate above it by the amount it is to shave off. The work is located in a nest on the top die, pushed through by a punch about the size of the bottom die, and stripped below that die. The edges are notched on those dies which take off a shaving thick enough to hang together so that it cannot form a complete ring. The notches are staggered in successive plates, as in the right-hand broach, Fig. 72. Air jets are the best means of clearing the shavings out of the dies. Jets may be led in over the several cutting edges by grooves on the under surfaces of the dies or by holes through spacers between the dies.

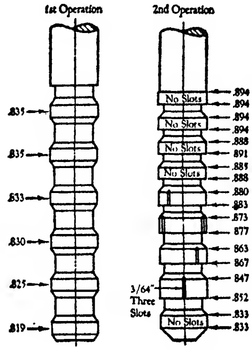


FIG. 72.—The first (left) and second (right) broaches, Fig. 71, showing typical broaching allowances.

The *pressure required* in shaving and broaching may be approximated as a swaging load upon the difference between the areas of the hole before and after the operation plus an allowance for friction.

Hot Punching.—Forging, or piercing and expanding the eye in picks, hammer heads, etc., represents a considerable part of hot punching practice. Fig. 73 illustrates a typical arrangement of punches and gripping dies for the three operation pick-eye forging shown. Two, three or four operations are used according to the depth of the eye and whether a low-carbon steel or a tool steel is used. The preliminary shape of the eye is forged in tools on the side slide of the press. In forging the eye, the hinged gripping dies are brought together and held tightly while the punches do the piercing. Because of their tapered noses, these punches force a considerable portion of the hole scrap out into the side-walls of the eye. Thus the scrap finally forced out is only a small portion of the space volume of the finished eye. It may be noted that the points of the pick are worked out in a helve hammer.

In some hot hole-punching operations the die is fairly sharp edged whereas the punch has a considerable radius. This is because the punch is harder to keep cool than the die. Considerable burr forms on the scrap slug, following the radius of the punch, and is pinched off between the side of the punch and the die edge.

In other hot hole-punching through thick material it has been necessary to use a number of separate slugs or punches. These are dropped into a nest above the work, for location, forced through the work, and

dropped into water under the press to be cooled before being used over again.

Miscellaneous.—Blanking operations may be combined with other types of operations, and especially those of the drawing group. In the so-called "combination die" for blanking and drawing, used ordinarily

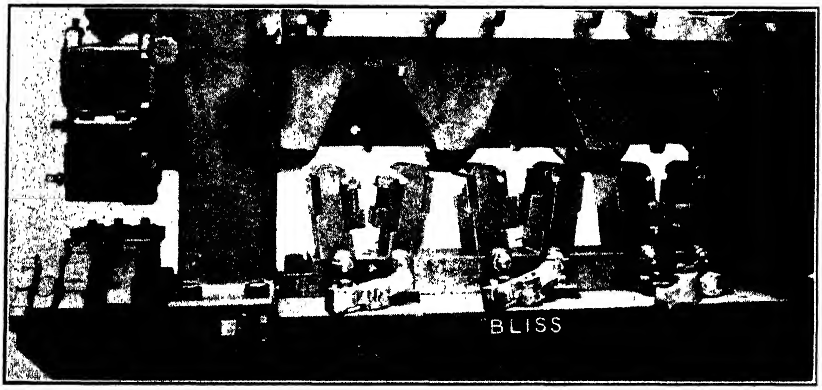


FIG. 73.—The method of gripping, piercing, and expanding (hot) the eye in picks, hammers, axes, etc.

in double-action cam presses, the blanking die ring is mounted on top of a drawing die as in Fig. 74. The blanking punch (at the right) is mounted on the blank-holder slide, and, after cutting, dwells to hold the blank, while the drawing punch at the left descends to draw the shell. Such dies are sometimes operated in double-action toggle presses also,

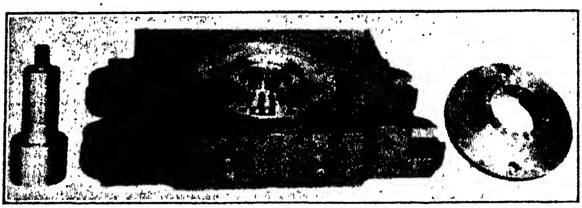


FIG. 74.—A steam-heated combination die for blanking and drawing paper caps.

but these presses are not really adapted to such work on account of the type of gibbing and possibly unbalanced actuating pressure on the four corners of the blank-holding slide.

When combination dies are used in single-action presses with air, rubber or spring drawing attachments, the blanking portion of the die is as before, while the drawing function is inverted. Thus the drawing

punch is on the die base and the blanking punch serves also as a drawing die. The blanking punch takes the form of a ring, mounted on the press slide. Its outer edge is ground sharp for cutting, and its inner edge is radiused for drawing. Thus every time it becomes dull and must be reground, the draw radius must be finished over.

The exact size of the blank for combination dies must usually be determined from approximate blanks by cut-and-try methods. For that reason the drawing portion of the die is often finished up ahead of the cutting edges. Cutting and cupping dies used in double-action

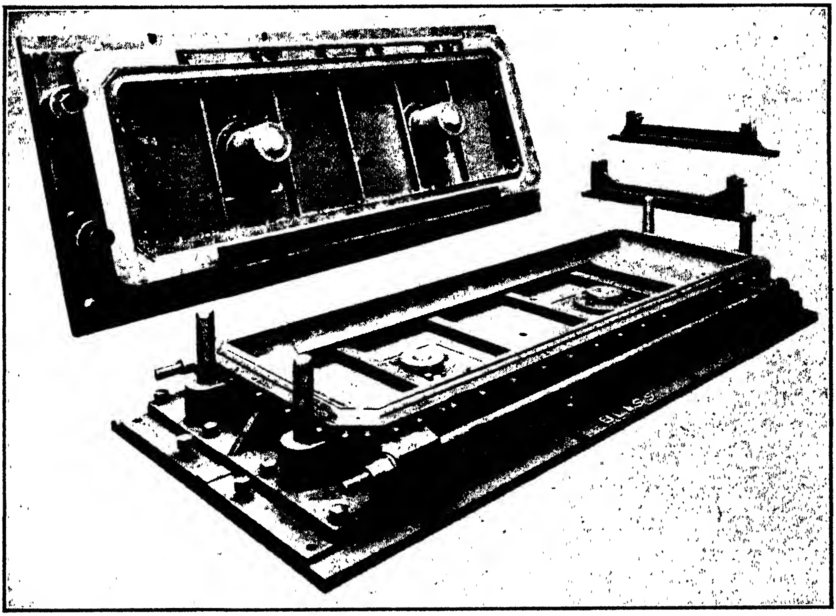


Fig. 75.—A vault-top trimming die adjustable to two lengths.

crank presses are similar to the above though less common. Cutting and stamping dies for can ends and the like also come into this group. All the combination dies will be considered in greater detail with drawing and stamping operations.

The die shown in Fig. 74 is interesting in that it is built into a deep die base cored for steam heating. The die is for blanking and drawing shallow paper cups for box caps, etc. Paper may be blanked in single sheets or a few sheets at a time in ordinary blanking dies, close fitting, however. But when a number of sheets are to be cut to shape it is necessary to use "hollow cutters" or knife-edge punches working against saw-steel or end-grain maple block. This is because, if a number of

sheets are cut in a plain blanking die, the upper and lower sheets will be cut to the correct size whereas the sheets between are likely to tear irregularly larger or smaller than the cutting edges, following the weak spots. The same thing applies to thick and loosely laminated cardboard and other materials of non-uniform strength.

Hollow cutters are usually strip steel forged to the outline, welded and ground to a knife edge. In some cases, particularly for small production, such cutters may be made up of thin, flexible steel band or strip, with one edge sharp, cut or bent and set into sawed grooves in hard wood. Gum rubber is tacked along the edges for stripping.

Some typical loads found in testing steel rule dies and hollow cutters are, for cutting:

Cotton glove cloth, independent of thickness, 240 lb. per in.
Kraft paper, test on 0.200-in. thickness, 385 lb. per in.
Celluloid, test on $^{11}\!/_{32}$-in. thickness, 300 lb. per in.
Warmed five minutes in water at 120 to 150° F.

Similarly, temporary blanking dies for cutting steel have been made up by setting standardized steels of simple shape in a cast holder in position to template, and securing them in non-shrinking babbitt poured around them and hammered after it has cooled.

Ordinarily, however, substantial construction is of first importance in blanking dies. In many cases the side thrust or spreading strain on the die steels approaches in magnitude the vertical shearing load.

Blanking and trimming dies are sometimes made adjustable where two shapes are very similar and the production is not large. Thus the vault top trimming die in Fig. 75 is adjustable to two lengths. The left end of the die is moved out, and one of the sections shown at the right is inserted. It will be noted that, to prevent spreading, a substantial steel tie-rod is provided down each side of the die.

CHAPTER V

BENDING OPERATIONS

THE operations which are collected in the forming group include bending operations of all sorts, bulging, beading, necking, flanging, burring, curling, wiring, and some shallow drawing or stamping operations. All these involve the plastic deformation of the metal, exceeding its elastic limit but not its ultimate strength. The movement of the metal is greater than in shearing but generally less than in drawing or in the squeezing group.

Metal Movement in Bending.—The formula for the strength of structural beams is based upon stressing the metal in compression on one side of the neutral axis of the section and in tension on the other

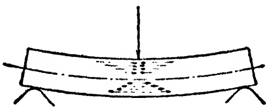


FIG. 76.—The beam formulae based upon elastic deflection with balancing tensile and compressive stresses set up each side of a central neutral axis.

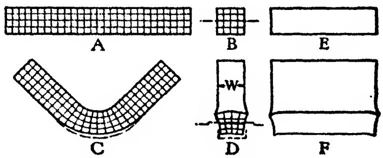


FIG. 77.—The natural distortion accompanying plastic deformation in bending.

side (the lower side), as indicated in Fig. 76. For uniform sections of rolled material the neutral axis coincides with the center line up to the elastic limit. If the load is increased, the stresses, particularly toward the upper and lower surfaces, increase beyond the elastic limit, causing permanent deformation of the material.

Thus, in Fig. 77, let us consider the unstrained bar to be made up of uniform cube-shaped crystals, just for illustration. The shape of the crystals may be changed, but their volume remains the same, within a fraction of 1 per cent, in any press-working operations. Consequently, when bent, the crystals on the tension side are stretched in the direction of the length of the bar. This reduces their cross-section area and therefore also their relative resistance to further stretching. On the compression side of the neutral axis the cubes are squeezed shorter, which increases their cross-section area and therefore also their resis-

tance to further working. (The total stresses mentioned here should not be confused with the true unit stresses, which increase, owing to strain-hardening, as the metal is worked.)

The increasing resistance of the material in compression and the relatively decreasing resistance of the material in tension causes the neutral axis to shift correspondingly toward the compression side. The cross-section of the bar is no longer square owing to the reduced cross-section of the crystals in tension and increased cross-section of those in compression, as shown at *D* in Fig. 77. Because of relatively decreasing resistance, the greater portion of the metal movement takes place on the tension side, resulting in an actual reduction in both thickness and cross-section of the bar over the radius, as indicated by the dotted lines in Figs. 77 *C* and *D*.

To demonstrate this we may take three experimental 90° bends made in quarter-inch annealed steel strips, as follows:

TABLE V

Inside Radius of the Bend, Inch	Final Thickness at the Bend, Inch	Inside Radius to Neutral Axis, d, Fig. 79
½	0.243	$0.42t$ [a]
¼	0.237	$0.40t$
⅛	0.234	$0.38t$

[a] $t = 0.250$ in.

The distance to the neutral axis was derived from the increased space between scratch marks on the outside surface and the decreased distance between scratch marks on the inside surface. Although this method does not give precise results it is sufficiently close for illustration.

The smaller the radius of the bend relative to the metal thickness, the greater is the stretching and consequent reduction in metal thickness over the radius.

The wider the bar or strip is, relative to its thickness, as in bending sheet metal, the less it can distort across the compression side (*W* in Fig. 77 *D*), and consequently the greater is the tensile distortion and reduction in thickness.

By using an appreciable radius instead of a sharp-corner bend, the blank is shorter and harder-rolled material may be used as the bend is less severe. Both points become of importance when the quantity to be produced is very large. The effects of radius and temper or hardness upon bending properties are well illustrated in Table VIII.

If there is tension on the bar or strip, due to a blank-holder or to the making of other bends simultaneously, the deformation in tension at the bend will be even greater relative to that in compression, and the thickness will be reduced even more.

Another interesting effect of an outside tension upon a bend has been pointed out by H. A. Freeman in *Machinery*. In winding wire or strip upon a mandrel there is a tendency to form a bulge or buckle at the first bend, as shown in Fig. 78, because the local stresses are lower when spread around the greater radius.

Sufficient tension on the strip while bending, however, will give quite a sharp bend and eliminate the buckle.

As illustrated at *A*, the balancing tensile and compressive stresses at the section x–x in the normal bend plus the outside tensile force *B*

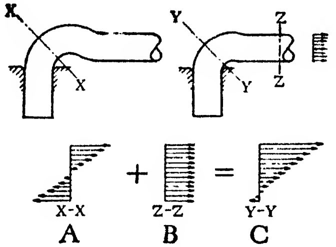


FIG. 78.—Use of tensile stress in the material to give a sharp bend as in spring winding. (*Freeman*)

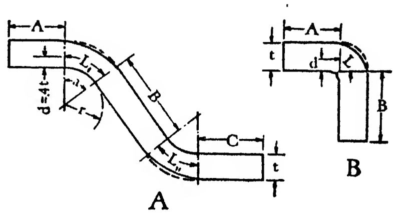


FIG. 79.—Approximate location of the neutral axis in determining the length of metal to be allowed for a bend.

gives a stress across the section y–y which will produce the sharp bend illustrated at the right.

Figs. 76 and 78 illustrate the stresses across the section of the part subject to bending, as graded uniformly from zero at a central neutral axis to maximum values at the extreme fibers. This is satisfactory for structural purposes where beams, etc., must not be loaded beyond their elastic limits, and the maximum compressive and tensile stresses will be approximately equal and lower than the elastic limit.

In bending, as in Figs. 77 and 79, however, the metal must be stressed to, and beyond, its yield point from the extreme fibers to the neutral axis as all the metal is being moved plastically and the neutral axis actually shifts from the center line toward the compression side during bending. The stress diagram and the beam formula should then be revised based upon stresses rising on both the tension and compression sides, from the yield point of the metal at the neutral axis to a value which may and frequently does approach the true (not nominal) ultimate strength of the metal in the extreme fibers. Quarter-hard,

half-hard and harder tempers are often used for bent parts in order to obtain maximum stiffness. Accordingly the initial yield point, and therefore the stress at the neutral axis, is likely to be quite high. Selecting the hardest temper that the metal will stand on a given bend, without failure (see Table VIII), means that the true ultimate strength is very closely approached in the extreme fibers. Evidence of this is that an occasional piece which is harder than specified will show tensile fractures on the outside of the bend.

The length of strip or bar (L in Fig. 79) to be allowed for making bends, when cutting blanks, depends upon the inside radius (r), the angle of the bend (a) and the thickness of the metal (t). As has been pointed out, the amount of stretch, and therefore the final thickness of the metal over the bend, are both affected by variations in the angle, the radius and the metal thickness and in some cases by the cross-section shape of the piece being bent. The allowance length L therefore is not a true arc at a distance $\frac{1}{2}t$ from the die radius. A true arc is close enough for calculations, however, if it is taken at a radius $r + d$, where $d = 0.3t$ to $0.5t$. One manufacturer assumes $d = 0.4t$ (approximately) for all cases, and, referring to Fig. 79 A, writes the obvious formula:

$$L = (r + 0.4t) \times 2\pi \times a°/360 \tag{4}$$

Then the length of the blank for Fig. 79 is:

$$A + L_1 + B + L_{11} + C$$

For sharp bends, Fig. 79 B, the method of approach is the same, but as the inside radius has been reduced nearly to $r = 0$, the metal is stretched thinner over the corner than in almost any other case. If the right-angle sharp bend, Fig. 79 B, were made so that metal thickness was not reduced over the corner, as indicated by the dotted line, then d would equal $0.5t$, from which, by formula, $L = 0.785t$.

The manufacturer previously quoted gives $L = 0.4t$ as an approximate allowance for 90° sharp-corner bends. This would indicate $d = 0.25t$, although the reduction in thickness is not so great as this would suggest, for quite a bit of metal is stretched from the straight leg on each side.

Efforts to confirm this, however, seem to indicate that it is too low an allowance. A number of bends were made in a 90° V-die on 0.265-in. and 0.128-in. hot-rolled steel. The distance, d, to the neutral axis varied from $0.37t$ to $0.42t$, depending apparently upon how much coining was done to make the bend sharp. The location of the neutral axis was figured from the compression and stretch respectively of the

inside and outside lengths of each strip with a correction for the reduction in thickness over the corner which amounted to 13 per cent. The allowance, L, varied from $0.65t$ to $0.73t$. This checked up when figured by formula using $d = 0.4t$ plus an inside radius of 0.005 to 0.015 in., to compensate for the accumulation of metal in compression at the corner, Fig. 79 *B*.

Some portion of the original elasticity of the metal remains after any bend. Accordingly, as the pressure on the bending punch is withdrawn, those molecules in the bent strip which have been in compression expand slightly, and those which have been in tension contract slightly. The amount of the "spring-back" is given by C. C. Herman as follows:

TABLE VI

Low-carbon steel, bent hot	½° to 1°
Low-carbon steel, annealed	1° to 2°
0.40 to 0.50 C steel	3° to 4°
Open-hearth spring steel, annealed	10° to 15°

These figures are for strip material ¼ to ⅜ in. thick and presumably for a 90° bend over a uniform radius.

The amount of spring-back is undoubtedly greater for the greater angle of bend and proportionately greater for the smaller radius of bend. In addition it varies, as the above figures indicate, according to the analysis, rolling and treatment of the material.

There are two ways of taking care of the spring-back in order to get the desired angle. One is to over-bend the metal as illustrated with some exaggeration in Fig. 80 *A*. On account of the variable factors involved, the amount of over-bend must still be determined by trial or from similar cases. Thereafter there will be some variation due to non-uniformity of commercial material.

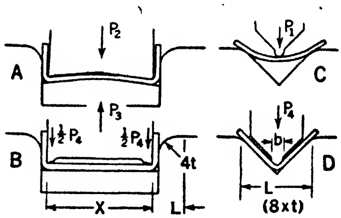


FIG. 80.—Overbending and striking to correct or counteract spring-back due to elasticity of the material. Effects are exaggerated.

The other method is to hit-home or bottom at the end of the bend to "set" the metal. In effect this is a coining operation, to set up compression strains in the metal, to counteract and balance the tensile surface strains of bending. Any hit-home operation is dangerous in that two blanks or a careless set-up will almost certainly break or strain some part of the press. The average bending die is made so that

it bottoms over a large area, and, instead of concentrating the striking pressure effectively at the radius, wastes it over the plain surface and is especially inefficient at the radius because the metal is thinner there.

In the V-die sharp-corner bends previously referred to, in order to obtain and to set a sharp bend, pressures were required which amounted to between two and four times the shearing strength of the strip across the bend. A very little increase in the squeeze increases the pressure very much.

Less pressure is more effective if concentrated right at the radius. This may be done by means of pressure beads little more than the metal thickness in width and located at the inside bending corner. See Fig. 80 *B* and *D* and formula 4*d*.

For approximating bending pressure only (but not including setting pressure to counteract spring-back), the following empirical formulae are based upon the beam formula, but the constants are increased in accordance with old experimental results to compensate for short spans and plastic working stresses.

S = nominal tensile strength of metal, pounds per square inch;
t = thickness of metal strip to be bent, inches;
w = width of bend, inches;
L = span (approx. $8 \times t$ for V-die), inches;
X = flat face, or inside width, for double bends, inches.

Bending pressure only, P_1 for V-dies:

$$P_1 = 1.33Swt^2 \div L \tag{4a}$$

Bending pressure, P_2, for double dies, including pad pressure:

$$P_2 = 0.67Swt\left(1 + \frac{t}{L}\right) \tag{4b}$$

Pad pressure only, P_3, to hold bottom flat during bending:

$$P_3 = 0.67Swt \tag{4c}$$

Bottom setting pressure, P_4, to counteract spring-back;

b = plan projected width of beads or contact lines, inches;
S_1 = setting pressure at 50,000 to 100,000 lb. per sq. in. for mild steel.

$$P_4 = w \times b \times S_1 \tag{4d}$$

"Grain" and "Temper" of Rolled Metal.—There is less tendency to get cracks or fractures around the outer radius when a bend is made across the grain of a hard-temper metal, as in Fig. 81, than when the same bend is made over the same radius but paralleling the grain.

Table VII shows that metal tested in tension, parallel to the direction of rolling, has been worked less and shows greater remaining ductility than that tested across the direction of rolling.

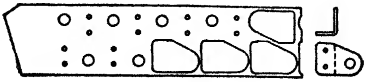


Fig. 81.—As the direction of rolling is the direction of greatest ductility, it favors severe bending and should be considered in blank layouts.

A pure metal may be quite severely rolled, then properly annealed, and the recrystallization will remove all directional properties. That is, the new crystals will assume approximately uniform dimensions with uniform properties in all directions. If cold rolling is then continued the crystals are worked out and elongated in the direction of rolling as shown by their old boundaries, Fig. 25 *B* and *C*. In this process, movement is occurring along more and more of the groups of crystal slip planes which happen to be favorably oriented with respect to the direction of rolling. It is to be expected then that further movement, as in a subsequent bending operation, will occur less easily along these slip planes than in some other direction which has been subject to less working.

Directional differences in the properties of rolled metals may also be due to working out impurities like the slag inclusions in wrought iron. This gives a distinctly fibrous character which annealing cannot remove. Alloys (brass) and aggregates (steel) also show strong directional properties which may readily be due to working out the less ductile phases, such as beta brass or pearlite in steel.

Table VII

THE EFFECT OF DIRECTION OF ROLLING IN TENSION TESTS OF ROLLED ZINC (Dr. Oswald Meyer)

Plate tested as received. Thickness Varied from 0.044 to 0.051 In.

Specimens Cut and Tested	With Grain	Across Grain
Stress at first permanent set, pounds per square inch	1,990	2,420
Yield point, pounds per square inch	11,400	13,640
(Nominal) Ultimate strength, pounds per square inch	30,400	36,800
(General) Elongation, per cent	27.2	9.7
Reduction of area, per cent	43	17

TABLE VIII

EFFECTS OF TEMPER AND DIRECTION UPON BENDING LIMITS

High Brass, Temper, B. & S. Numbers Hard	Thickness		Rockwell Hardness (1/16-In. Ball × 100-Kg. Load × Red Figures)	Minimum Suitable Radius of Punch		
	B. & S. Gauge	Inch		Bend Perpendicular to Direction of Rolling	Bend 45 Deg. to Direction of Rolling	Bend Parallel to Direction of Rolling
½ hard.......2	20	0.0319	67	Sharp	Sharp	Sharp
	18	0.0403	66	Sharp	Sharp	Sharp
	15	0.0571	68	Sharp	Sharp	Sharp
	14	0.0641	70	Sharp	Sharp	Sharp
	11	0.0907	73	Sharp	Sharp	Sharp
¾ hard.......3	24	0.0201	67	Sharp	Sharp	Sharp
	20	0.0319	71	Sharp	Sharp	Sharp
	16	0.0508	78	Sharp	Sharp	0.0156″
	14	0.0641	78	0.0156″	0.0156″	0.0312″
	11	0.0907	77	0.0156″	0.0312″	0.0937″
Hard.........4	30	0.0100	....	Sharp	Sharp	Sharp
	24	0.0201	76	Sharp	Sharp	Sharp
	22	0.0253	79	Sharp	Sharp	Sharp
	20	0.0319	80	Sharp	Sharp	0.0156″
	18	0.0403	82	Sharp	Sharp	0.0312″
	17	0 0451	83	Sharp	0.0156″	0.0625″
	16	0 0508	84	Sharp	0.0156″	0.0937″
	15	0.0571	83	0.0156″	0.0312″	0.0937″
	14	0.0641	82	0.0312″	0.0312″	0.0937″
	12	0.0808	82	0.0312″	0.0625″	0.0937″
	11	0.0907	84	0.0937″	0.1250″	*a*
	10	0.1019	81	*a*	*a*	*a*
	9	0.1144	84	*a*	*a*	*a*
	....	0.1250	80	*a*	*a*	*a*
Extra hard....6	24	0.0201	83	0.0156″	0.0312″	0.0937″
	20	0.0319	85	0.0312″	0.0625″	*a*
	19	0.0359	87	0.0625″	0.0937″	*a*
	18	0.0403	87	0.0625″	0.1250″	*a*
	17	0.0451	88	0.0625″	0.1250″	*a*
	16	0.0508	88	0.0625″	0.1250″	*a*
	15	0.0571	88	0.0937″	*a*	*a*
	14	0.0641	89	0.1250″	*a*	*a*
	13	0.0719	89	0.1250″	*a*	*a*
	11	0.0907	87	*a*	*a*	*a*
Spring........8	30	0.0100	....	Sharp	0.0156″	0.0937″
	26	0 0159	....	0.0156″	0.0625″	*a*
	24	0.0201	88	0.0312″	0.0937″	*a*
	22	0.0253	90	0.0312″	*a*	*a*
	20	0.0319	88	0.0312″	*a*	*a*
	18	0.0403	92	0.0625″	*a*	*a*
	16	0.0508	90	0.0937″	*a*	*a*
	14	0.0641	92	0.1250″	*a*	*a*

[a] None of the radii tested were suitable.

The effect of directional properties of high brass upon the maximum sharpness of the bend is illustrated in Table VIII. This is reproduced from the interesting experimental bending work[1] of Straw, Helfrick and Fischrupp. Their tests were performed with a V-die and a series of interchangeable V-punches each with a different radius. Samples of strips of varying thickness and hardness or temper were cut with the grain, at 45° to the grain and across the grain. The table gives a record of the sharpest (least) radius that could be used in bending these sample strips, without causing visible fractures on the outside or tensile surface of the bend. The nominal analysis of the brass is given as alloy 1 under Table IX.

Table VIII also shows well the effect of "temper" upon the sharpness of the bend to be produced. Temper refers in this instance to the hardness or stiffness of metal for fabricating purposes, produced by cold-rolling or strain-hardening. It is usually desirable to have as stiff a product as possible, produced from as thin metal as possible for economy. The temper should be such then that the blank will stand, without fracturing, the additional strain-hardening which is involved in bending or otherwise plastically working it into final shape.

Table IX shows the relation of temper, hardness and amount of cold-

TABLE IX

TEMPERS AND HARDNESS OF SOME COLD-ROLLED COPPER-ZINC ALLOYS[a]

Reduction by Cold Working		Temper, Brass Practice	Average Rockwell Hardness ($\frac{1}{16}$-In. Ball × 150 Kg. Load × Red Figures)						Nominal Ultimate Tensile Strength (High Brass), Pounds per Square Inch.	General Elongation (High Brass), Per Cent in 2 In.
B. & S. Gauge Numbers	Per Cent (Approximate)		Brass		Nickel Silver		Phosphor Bronze			
			1	3	4	5	6	7		
Annealed	0	Soft	....	....	....	....	....	....	47– 49,000	67
1	10	¼ hard	....	59	....	....	....	....	51– 53,000	46
2	20	½ hard	69	67	50	66	39	60	57– 60,000	28
3	30	¾ hard	74	....	....	....	....	....	66– 68,000	17
4	40	Hard	82	....	56	72	62	75	70– 77,000	11
6	50	Extra hard	87	....	....	76	69	....	84– 86,000	10
8	60	Spring	90	....	....	....	73	81	94– 98,000	9
10	70	Extra spring	....	....	....	....	....	82	101–108,000	8

[a] Prepared from Technical Publication 406, A.I.M.M.E. by Straw, Helfrick and Fischrupp. Physical properties from test data by R. S. Pratt.

Nominal Compositions

Alloy No. 1, High Brass: Cu 66, Pb 0.30, Zn 33.5.
Alloy No. 3, Brass: Cu 65.5, Pb 0.95, Zn 33.55.
Alloy No. 4, Nickel Silver; Cu 72, Zn 10, Ni 18.
Alloy No. 5, Nickel Silver: Cu 55, Zn 27, Ni 18.
Alloy No. 6, Phosphor Bronze; Cu 95.7, Sn 4.3, P 0.20.
Alloy No. 7, Phosphor Bronze: Cu 92, Sn 8, P 0.15.

NOTE: Compare this table also with Fig. 127, p. 135.

[1] W. A. Straw, M. D. Helfrick and C. R. Fischrupp, "Forming Properties of Thin Sheets of Some Non-ferrous Metals," Technical Publication 406, A.I.M.M.E., Feb., 1931.

working on a scale employed by brass makers. Thus a "hard" brass is cold rolled four numbers on the Brown and Sharpe gauge scale, reducing it about 40 per cent in thickness. The Rockwell hardness given is an average in most cases of a number of values. The rate of strain-hardening is necessarily different for different metals and alloys, as the table suggests.

In each case as the metal is cold-worked or strain-hardened to a greater and greater extent there will remain a smaller and smaller margin before all available slip planes are used up and fractures occur. This smaller remaining margin for further cold-working will naturally limit bending operations to easier and easier bends. The sharpness of the bend relative to the metal thickness, clearly determines the severity of movement in the immediate locality of the bend.

Table X shows the accepted tempers for aluminum and corresponding values of tensile strength and elongation to indicate the rising stiffness and reducing ductility respectively as the metal is strain-hardened. The Aluminum Company numbers 2S and 3S designate two common commercial grades, the latter containing 1¼ per cent manganese as a hardener.

Table X

TEMPERS OF ALUMINUM [a]

Reduction by Cold Working		Temper, Aluminum Practice	Nominal Ultimate Tensile Strength, Pounds per Square Inch		General Elongation Per Cent in 2 In.		Brinell Hardness	
B. & S. Gauge Numbers	Per Cent (Approximate)		2S	3S	2S	3S	2S	3S
Annealed	0	Soft	12–16,000	15–18,000	30–45	15–30	23	28
2	20	¼ hard	14–18,000	16–20,000	5–10	5–8	....	....
4	40	½ hard	16–20,000	19–24,000	3–7	2–6	32	40
8	60	¾ hard	19–23,000	24–29,000	1–4	1–4	....	....
14	80	Full hard	22–26,000	27–32,000	1–4	1–4	44	55

[a] From data in the "Mechanical Engineer's Handbook," third edition, Part 6, by Lionel S. Marks, McGraw-Hill Book Co., New York.

It will be noted that tempers used for aluminum do *not* refer to the same amounts of cold-working as tempers used for brass. Tempers for steels are different from either of these, and in no case does the scale of tempers indicate the plastic limit. This would indeed be impractical under such a system, as the amount of cold-working which is possible, as well as the rate of strain-hardening, seems to vary with each alloy.

Table XA gives an idea of common tempers for low-carbon cold-rolled steels. Variations in mill and rolling practices make it impossible to give anything more definite at this time. This table shows very well the effect of temper upon bending.

Table XA

COLD-ROLLED STRIP STEEL SPECIFICATIONS

(*Stanley Works Handbook*)

Temper	Arbitrary Temper Index	Ultimate Tensile, Pounds per Square Inch	General Elongation, Per Cent in 2 In.	Notes
Dead soft...	6	40,000	....	Selected for extra deep drawing.
Dead soft...	5	40,000	Min. 33–40	For bending, forming and shallow drawing.
Planished....	4	40,000	Min. 30–39	Will unwind from coils without kinking. 180° bend either way.
¼ hard.....	3	45,000	Min. 15–20 Max. 30–39	180° bend across grain. Sharp 90° bend with grain.
½ hard.....	2	55,000	Min. 5 Max. 15–20	For easy blanking. Sharp 90° bend across grain. Rounding bend only, with grain.
Hard........	1	60,000 minimum values	....	Flat work only, where no bends are required.

Bending Operations.—Bar-folders, brakes, drawbenches, roll-forming machines and bending dies in presses share the field. Bar-folders, usually hand operated, grip the piece of tin plate or light-gauge steel and bend it back on itself to any desired angle. Brakes are regularly power machines built like a light C-frame or straight-sided double-crank press with a narrow bed. They are usually fitted with a 90° V-die the length of the press and arranged to clear various combinations of bends, the bends being made one at a time in any strip or sheet which is shorter than the die. Brakes are used for many operations in the manufacture of metal furniture and door trim, roofing, etc.

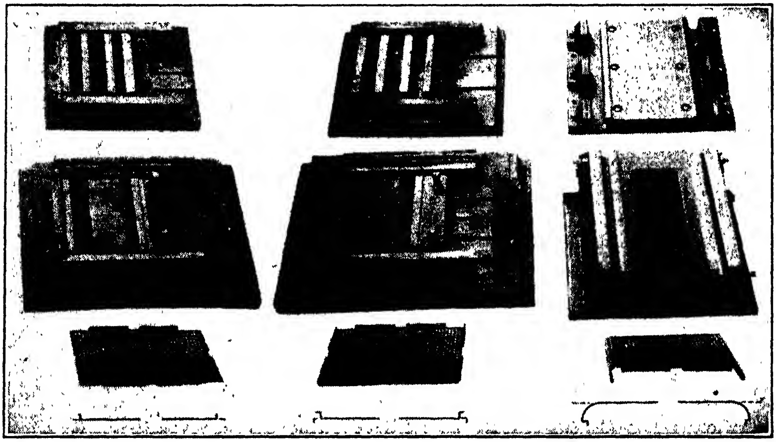
Where one shape is to be produced from strip metal in straight lengths and considerable quantity, as for mouldings, metal sash and trim, etc., either draw benches with suitable dies or rolling machines with a series of developed rolls may be used. Both have peculiarities which make them studies by themselves.

Bulldozers and hydraulic presses fitted with dies are widely used for the job bending of heavy bars, rails, rolled sections, etc., the work usu-

ally being done hot. Uniformity of results in hot bending depends to a considerable extent upon the care of the operator in heating and handling.

Power-press bending takes in a wide range of operations in direction, number of bends and methods of bending. Quantity is essential. And as most bending dies are necessarily arranged to strike solidly over a considerable area, care is required on the part of both the operator and the die-setter. The variety of ways of making bends, and of holding the metal against creeping, is such that a comprehensive view is best given by discussing a collection of dies.

Fig. 82 shows an interesting series of simple bends in the production of the heater jacket top shown at C. This top interlocks with four



A B C

FIG. 82.—Three adjustable dies, progressively bending the flanges of a jacket top to interlock with other jacket parts.

other sections of the jacket and consequently has hooks around the four sides. Being in the nature of a furniture job the bends must be accurately made. As the jackets come in several lengths, one pair of steels in each of the first two dies is made adjustable with pilot pins to assist in getting and maintaining alignment. The third die is made large enough for any length as it bends only along two sides. The first bend turns up a flange on the four sides, striking at the bottom, with an angle on the die steels of a little less than 90°, to correct for spring-back. In the second operation, as shown at B, the sheet is turned over, and a die, similar in general to the first, completes the double bend. Both dies are fitted with center spring-pads to hold the sheet flat and keep it from creeping while bending. The third die is fitted with hinged strips

to make the radius bend. These have only a small movement and are brought in tight by the wedges on the punch plate to give a positive over-bend.

Edgewise bending of sheet-metal blanks or strips may offer considerable advantage in economy of material, as in producing blanks for automobile side frame members and brake web members. It must be anticipated that the metal will become somewhat thicker where it is moving under compression strain, and thinner as it moves under tension, as illustrated in Fig 76, 77 *D* and 83. In making such bends there is a natural tendency to wrinkle in the compression areas and collapse or deflect where the metal is in tension. This must be overcome by very rigid holding. The wedge-action die shown in end view in Fig. 83 is a

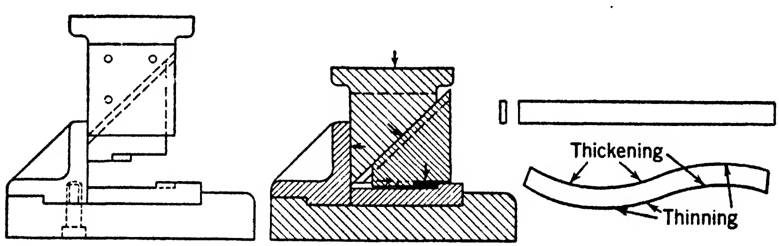


FIG. 83.—An edgewise bending die combining bending pressure with a holding pressure which compensates for non-uniformity and change of metal thickness.

clever solution to the problem in that it furnishes a self-adjusting blank holding action which takes care of variations in thickness of the original blanks, as well as changes in thickness during bending. A 45° angle on the wedge surfaces is reported to give a satisfactory ratio of holding pressure to bending pressure. A heel must be provided to support the punch and balance the side thrust, unless a double die is made using two opposite-moving wedge members to balance the strain. Vertical edgewise bending of blanks, singly or in packs, has been done successfully with proper provision for holding under a pressure equal to or greater than the bending pressure and with provision as well to take care of non-uniformity of original metal thickness.

Fig. 84 shows one of the operations in bending a step hangar or running-board support. There are two points of interest in this job: one, the large-radius bend in the channel; and the other, the flanged portion of the channel whereby it is attached to the chassis. There are four bends in this latter portion, and two being the reverse of the other two any error due to spring-back in the material is automatically compen-

sated for in angle and the flanges come out on the same plane. The spring-back does affect the distance across the flanges, however, so that for correct spacing the rivet holes cannot be punched until after bending.

Such an observation may be made of bending in general. Punched holes in different planes or sections of a formed article, to be in correct relative positions, should ordinarily not be punched until after the bending operations. There is too much opportunity for slight variations

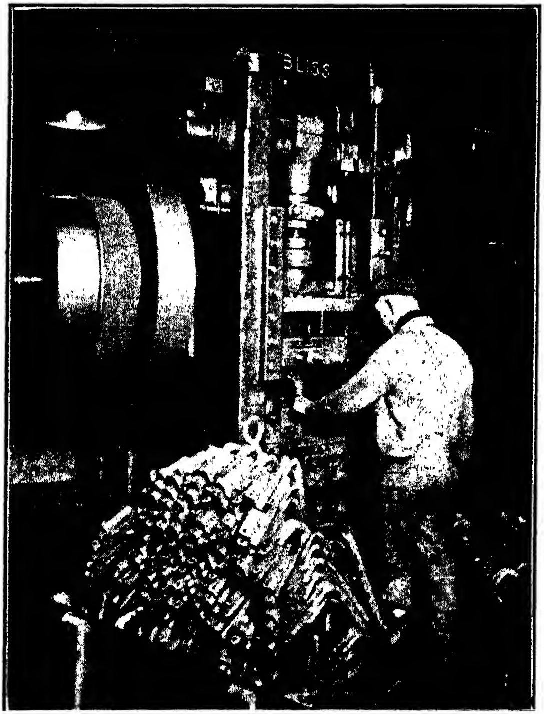


Fig. 84.—A running-board support pierced, after forming for correct hole relationship.

due to slippage or non-uniformity in thickness or physical properties of the material.

The bending of rolled channel sections always requires care and close confinement of the legs or flanges of the channel. Otherwise the extreme tensile or compressive strains in the flanges (depending upon the direction of the bend) will cause them to collapse or wrinkle, respectively.

"Bending in air" has been applied to describe such work as is shown in Fig. 85. The punch is a simple block, fitting the inside of the bread

pan, and arranged to start the edges or flanges for the subsequent wiring operation. The die is mounted on a manually operated slide plate for use on a relatively short-stroke wiring press. The blank, with the corners notched, is placed against side and back gauges shown on the die. As the punch enters, starting the bottom bends, surplus metal at the corners finds its way out into loops as shown, through corresponding slots at the corners of the die. These loops are subsequently bent tight against the ends of the pan.

Slide plates may readily be interconnected with the press control mechanism in such a manner that the clutch cannot be tripped unless the die is back and in correct location under the punch. In some cases slide plates are actuated mechanically by the press through cams

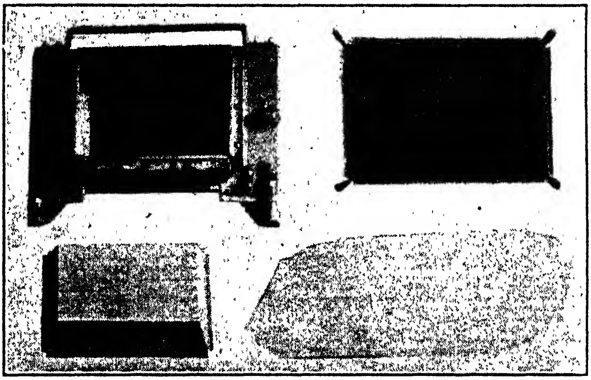


FIG. 85.—Bending in air. Corners of bread pan formed into loops in a die mounted on a slide plate.

or toggle levers. On large presses they are operated by air cylinders. The object, of course, in using sliding dies is to perform operations on shells of such depth, relative to the press stroke, that they could not be removed from the die while it is under the punch, Fig. 111.

Fig. 86, a relatively simple wedge-action die on a foot press, illustrates a combination of vertical and transverse actions. Two lugs on each side of the cap are to be bent in and then closed tight on a sealing strip. The transverse slides, which do the preliminary bending by means of horns extending to the front, are well gibbed in the die base and are held apart by springs. As the press slide descends, the wedges force in the transverse slides for their operation, and then allow them to retire before the center punch reaches bottom to complete the job. As the press slide moves up again, the wedges necessarily move in and out idly.

In many cases the wedges or cam pieces are so developed that they drive on both surfaces, giving practically positive action, independent of springs, to the transverse slides. The timing may be arranged so that one slide comes in and retires before another, where the two might otherwise interfere. The wedges should usually be extended sufficiently so that the leading portions enter the die base below the slides as pilots and brace before the slides are set in motion. Wedges are often made

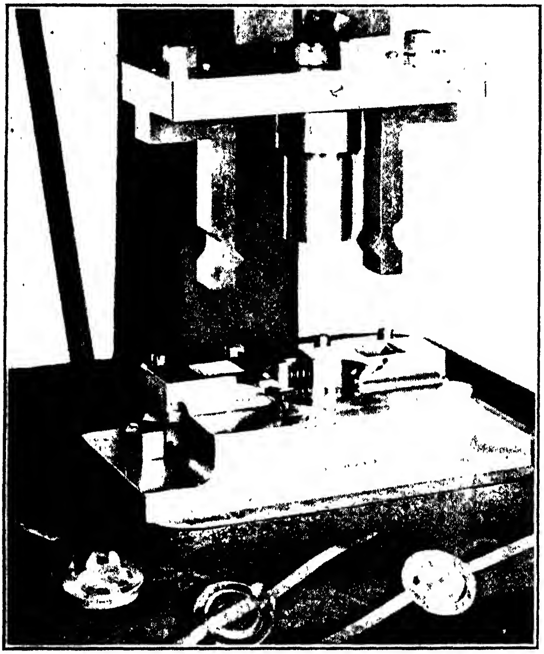


Fig. 86.—Lugs on each side bent part way down by wedge action and squeezed tight by the center punch.

of round stock with the sides slabbed off for short wedge movements. The machining is less expensive than for rectangular cross-sections.

The die shown in Fig. 87 performing a double curling operation is of interest chiefly in the method of obtaining the side motions. Each of the side slides is provided with a set of "knuckle-joint" links or toggles which are caused to straighten out by pressure on the rolls provided on the center pin. The desired pinch is obtained by adjusting the positions of the blocks carrying the outer pins, through set-screws at each end of the holder. The springs shown have leverage on the rear links to open the slides.

When substantially constructed, a knuckle-joint mechanism is capable of exerting a very high pressure at the end of its stroke, with comparatively little operating effort. This is due to the high mechanical

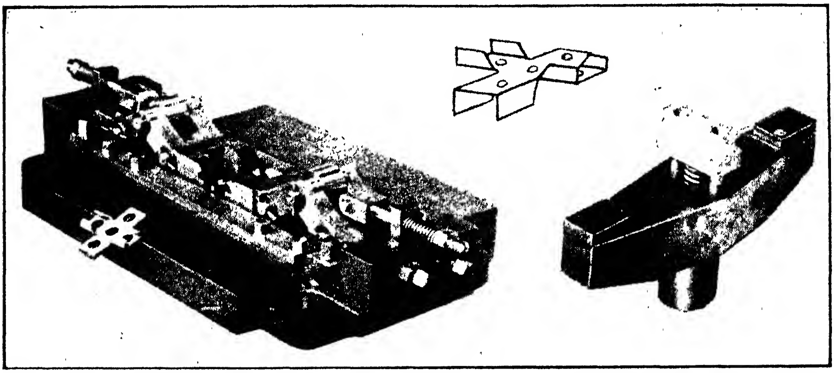


FIG. 87.—A powerful double side-thrust obtained through the increasing mechanical advantage of knuckle-joint motions.

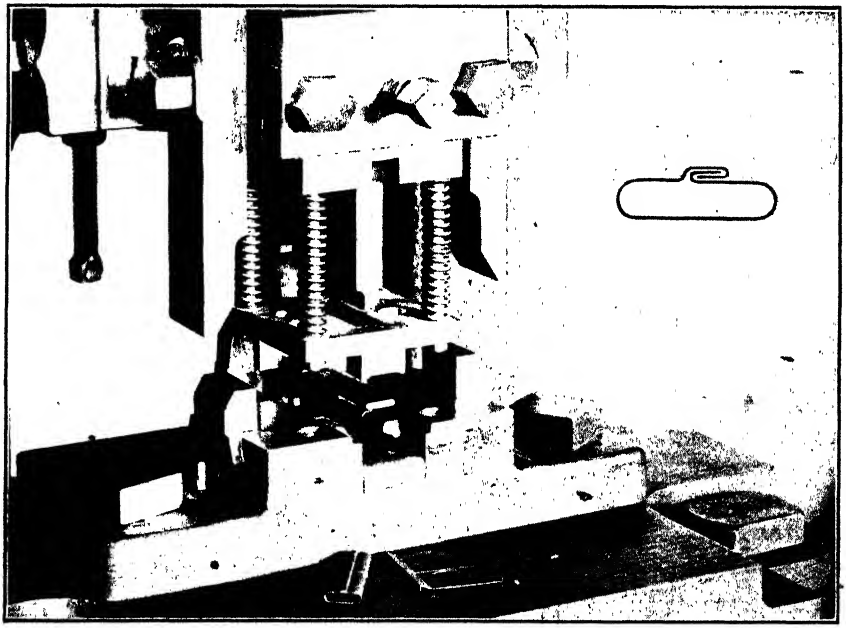


FIG. 88.—Floating mandrel and wedge motion combined to form and lock a tube.

advantage at the nearly straightened position of the links. The same principle is the basis of design of heavy-duty coining and swaging presses.

Fig. 88 shows an interesting combination of a floating mandrel, spring bending, wedge bending and positive closing. The previously formed blank, with hooks prepared, and the finished tube, having a regular lock seam, are shown on the bolster. The floating mandrel which fits the inside of the finished tube is actuated through a heavy spring directly from the press slide. As the slide descends, the mandrel strikes the blank and, by the pressure of the spring, forms it up into a U. Next the wedges force in the side slides which close in the sides

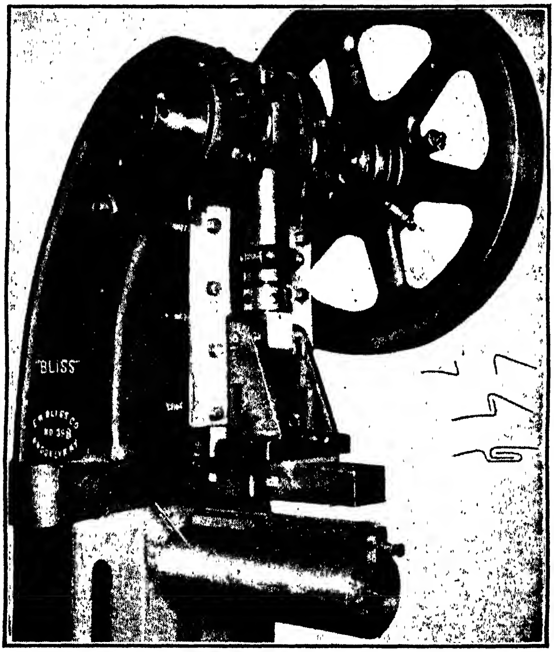


FIG. 89.—Forming and closing a lock seam on a duplex horn.

of the U to form the tube. Finally the center punch, attached directly to the press slide, strikes to close the hooks into the lock seam.

The lock seam is used to hold together the bodies of many pails, boxes, cans, barrels, tubes, etc. It is entirely a bending job. Thus, as shown at the right in Fig. 89, the first step is to form the hooks, one up and one down. Then these are hooked together and finally bent down with a blow, which closes them tightly and at the same time forms an offset in the body on one side or the other to prevent unlocking.

The simplest method of producing a lock seam is to form the hooks separately in a bar-folder, hook them by hand and close them with a plain horn and force or a seam roller. The next method, illustrated by

Fig. 89, is the use of the "duplex horn." The long steel, mounted on springs in the horn, is arranged for bending the two hooks simultaneously between its lower surfaces and the horn. These are then hooked by hand and closed at the next stroke of the press, between the force and the upper surface of the steel. More often this steel, incorporating the duplex feature, is built into the force instead of the horn.

For larger productions the automatic lock seamer forms the hooks and closes the seam in a single stroke. Beyond this are automatic can bodymakers which also form the bodies and perform other operations, at high speed, Fig. 101.

Flat blanks may be formed into a cylindrical shape as for bushings, etc., in one, two or more operations according to the case. Thus the principles of the floating mandrel and wedge die, Fig. 88, may be applied to U-ing, bending in the wings and closing down in a single operation.

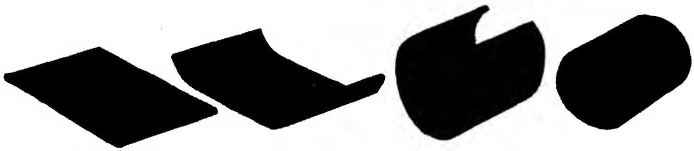


Fig. 90.—Three-stage forming of cylinders to eliminate flat portions; 3/8-in. steel plate.

Some straight and taper spouts, tubes, etc., are made following this principle, but the dies are rather expensive and complicated.

The handle of the stove shovel, Fig. 91, is made in two operations. In the first operation, which strikes the flat blank into the shape of the shovel, the handle portion is formed into a U shape. The semicircular punch and die at the right are then used to close the legs of the U into a cylinder. It will be found, however, that tubes formed in this manner are not truly circular but are flat for an appreciable space each side of the joint.

In Fig. 90, a 3/8-in.-thick motor frame, this flatted condition, which is also observed in cylinders formed in bending rolls, has been cured by inserting a preliminary operation. In this operation the troublesome portions near the ends of the blank are stamped to the desired radius. The blank is then U-ed as shown, in such a manner that the punch will just clear the previously formed ends. Finally it is closed in half-cylindrical dies and usually over a floating mandrel with provision for stripping. The elasticity of the metal causes the cylinder to open up somewhat after forming. This may be largely cured by restriking with considerable pressure while rotating on a mandrel. It is also claimed that well-closed cylinders may be obtained by striking the end radius

in the first operation to something less than that desired, and then, in the final operation, the cylinder is closed over a mandrel and to a diameter somewhat less than that required, with sufficient force to compress the metal beyond its elastic limit.

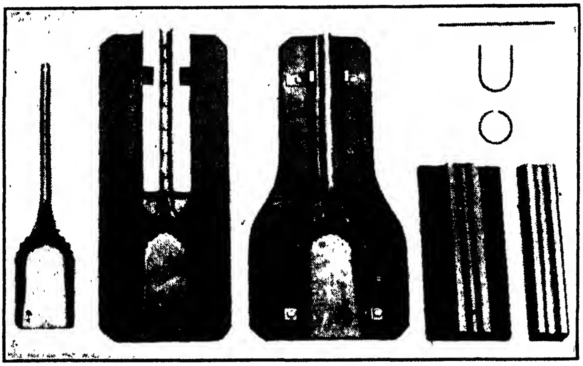


FIG. 91.—Stamping a shovel and U-ing the handle in one step, then closing the handle in a second step.

Fig. 92 and the shovel portion of Fig. 91 illustrate what may be called stamping. It is hit-home work in which the pressure exerted is little more than enough to bend or fold up the metal. When the need for a holding pressure and the prevention of wrinkling enters, the operation becomes shallow drawing. There are also operations in which intense coining pressures are required to bring out sharp lines and

FIG. 92.—Stamping, forming-up and closing a handle in three stages.

designs. It has been pointed out that hit-home operations result in a wide range of working pressures dependent almost entirely upon die-setting and possible variations in material thickness. Average intensities of one to a hundred tons per square inch may be found in successful practice. And two or three hundred tons may be the limit in some cases of accident.

CHAPTER VI

EXPANDING, CONTRACTING AND CURLING

Plastic movement of the metal in tension, compression or both is involved in all the miscellaneous group of operations which follows. None of them fall in the drawing or squeezing groups, nor yet can they be classed as bending. Most of them are commonplace in the manufacture of kitchenware and of cans and containers, though they have also found many uses elsewhere.

Bulging.—In the cases of many pitchers, kettles, pots, shaker tops, tubes, shells, boxes, etc., it is necessary to bulge or expand the walls of shells, which have been drawn up to that stage with straight walls. Bosses or other shapes may be forced out upon occasion. Pieced ware, can bodies, etc., may be bulged to the extent of narrow beads or rings, but little more, owing to the danger of opening up the seams.

The limitation upon bulging, as in other operations, is the amount of cold-working the metal will stand before it fractures. An increase in circumference (or diameter) of about 30 per cent in one operation is the most that is ordinarily expected of the ductile metals in the annealed state. This includes low-carbon steel, alpha brass, copper, aluminum, and silver particularly. The "per cent elongation in 2 in." of the metal is an index to its bulging limitations. The portion of a drawn shell which has been severely cold-worked in drawing must be annealed, of course, for a severe bulge. An excessive bulge may be accomplished in two or three steps with intermediate annealings, even using the same die with different settings.

The act of bulging a shell (from an original diameter D, to a maximum diameter D_1) naturally reduces the metal thickness (from an original thickness t to a minimum thickness t_1 at the diameter D_1). The relation may be expressed approximately as:

$$t_1 = t\sqrt{D/D_1} \tag{5}$$

Similarly, any surface area A is increased to A_1 at any increased diameter D_1:

$$A_1 = A\sqrt{D_1/D} \tag{6}$$

If the metal thickness did not change, the overall height of a cylindrical shell, bulged to a spherical shape (Fig. 94, A and B), would be reduced by an amount:

$$h_1 = (D_1/D - 1)\sqrt{D_1^2 - D^2} \tag{7}$$

This relation develops directly from formulae for the surface areas of cylinders and sections of spheres. But since the metal does become thinner as the diameter increases, there is a net increase in total area, and the reduction in overall height is less than that indicated above (by perhaps a third, for a 30 per cent increase in diameter). Changes in thickness and height are naturally altered by non-uniformity of

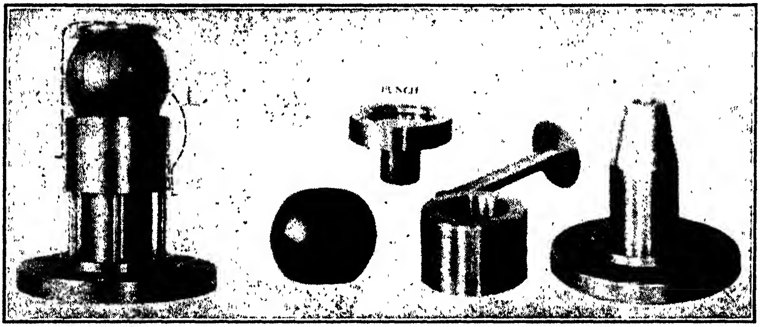


Fig. 93.—A segmental bulging die which expands as the punch forces it down upon the taper. Springs under the bed return it.

material and by frictional restrictions to free flowing so that, for close results, "cut and try" methods must supplement theory.

Fig. 93 shows a segmental bulging die both assembled and disassembled. The segments are held together in a group by springs around their top and bottom ends. When assembled, they rest upon the taper of the base and upon the stripping collar which is in turn supported by means of pins through the bolster and upon a substantial spring pressure attachment in the bed of the press.

The drawn shell is placed over the die as shown by dotted lines at the left in the assembled view. The punch, shown inverted with the disassembled parts, then descends. First it reduces the step at the radius of the shell, and then continues, compressing the springs under the bolster and forcing the shell to expand, as shown by the dotted line at the right, as the segments move down on the taper.

The segments naturally separate as they move out, which results in slight flats on the surface of the metal at corresponding points. These

flats are negligible in many cases but may be apparent when the surface is polished. The formation of flats is therefore to be considered against this type of die. Upkeep and production rates favor it decidedly.

The idea of an inside, wedge-motion punch may be adapted on occasion to the bulging of bosses and knobs on the sides of drawn shells.

Rubber punches may be substituted for the segmental construction in many bulging operations, but in such cases the die must be arranged to close around the piece completely. Then the metal is expanded to fit the inside shape of the die, giving a smooth true outline which would not be obtained without such confinement. Rubber dies are usually limited to relatively small productions as the rubber expanding piece must be replaced every few thousand pieces. For such work specify "cylinder rubber," a special soft grade.

Fig. 94 shows two methods of closing the die about the work. At *A* and *B* is shown a double-action die for flangeless shells, arranged for use in a cam press or a toggle press. One half of the die is mounted on the bolster and the other half on the blank-holder slide so as to form a closed cavity about the shell before the punch begins to expand it. Such a die may be inverted for use in a single-action press, in which case the die is mounted on the slide, the punch is on the bolster and the closing ring is carried upon pins from a spring pressure attachment under the bolster.

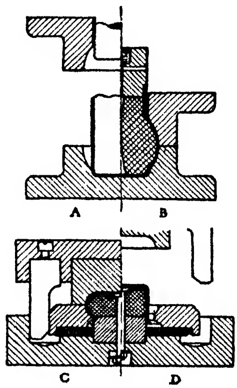


Fig. 94.—A double-action die and a wedge-motion die for bulging with rubber.

At *C* and *D*, Fig. 94, are open and closed views of a wedge-action die for rubber bulging. The sliding members which close in about the shell may comprise two or three sections, each with an operating wedge. The rubber punch may be either on the bed or slide of the press. In the latter case the die completely surrounds the area to be bulged. One other possibility in this field is the hand-closed, hinged die which is necessarily slower. In some instances as in Fig. 95, it is desirable to use hand closing with the double-action construction to lock the die together.

Hydraulic bulging is suited to quite intricate shapes, including bent parts, side bosses, tapers, etc., but is quite fussy owing to volume and pressure control, venting and leakage. In place of oil or soapy water some use small (0.030-in.) hard steel balls (as made by Pangborn Corp., Haegerstown, Md.).

The pressure (P) to be applied for hydraulic (and rubber) bulging

operations, expressed in pounds per square inch of the punch area, may be taken approximately as:

$$P = 2S \times t_1/D_1 \tag{8}$$

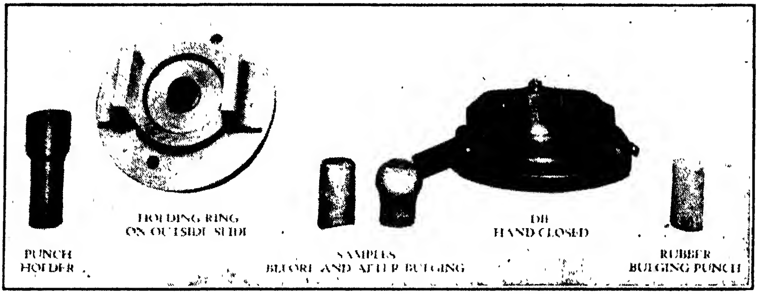


FIG. 95.—Note, in this double-action bulging die, that the rubber is held into the punch holder around its edge with no bolt through it, and that a steel sleeve protects its entry into the shell.

In this, t_1 is the final metal thickness in inches, D_1 is the shell diameter after bulging in inches and S is the tensile stress in the metal in pounds

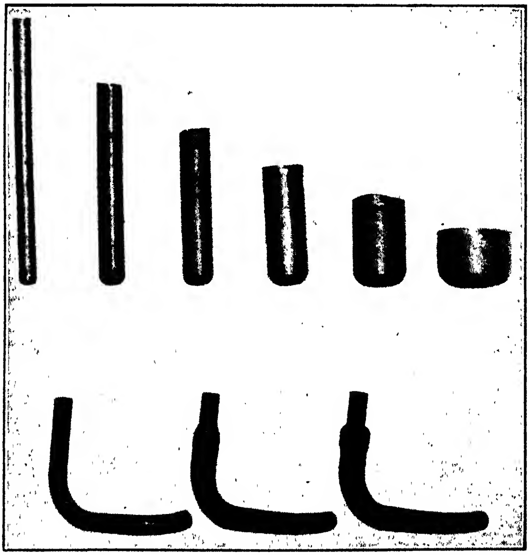


FIG. 96.—A shell drawn regularly in six steps and then bent, bulged and rebulged hydraulically in three steps with intermediate annealings.

per square inch. The value for the tensile stress varies above the elastic limit and toward the ultimate strength as the material is hardened by

working. The formula follows the same derivation as that for the bulging strength of pipe.

Hydraulic bulging and bending dies, like rubber bulging dies, must completely surround the work, confining the extent of the bulge. The dies must be split to remove the work and may be clamped together either by a toggle hand clamp; a screw, Fig. 97 *A*; a single-action cam press; or the blank-holding slide of a double-action press, Fig. 97 *B*. In any case it is important that air vents, *v*, be provided in the die to permit the escape of air as the shell is expanded filling the space about it. The bursting strain to be withstood by the die and the clamping mechanism is equal to the vertical projected area of the working cavity multiplied by the bulging pressure per square inch as found above, or more if the plunger is capable of building up an excessive pressure at the end of its stroke.

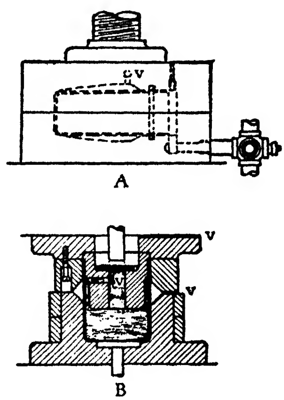


FIG. 97.—(*A*) A screw-closed hydraulic bulging die controlled by valves, and (*B*) a die closed by the outer slide of a double-action press, the pressure being applied by the inner slide.

The working pressure may be applied directly by the crank motion of a press, or through pipes and valves from an accumulator, or a force pump with a relief valve. A force pump is hardly economical because of the large percentage of time it is pumping into the waste. Fig. 97 *A* illustrates a screw-clamped die with valve control arranged to fill from the city pressure, bulge with accumulator pressure and then empty to waste. Pipe lines and valve must be large relative to the work for quick action.

When bulging is done in simple single-action presses with hinged dies closed and locked by hand, the punch serves as pump plunger, and the volume of water (or oil) placed in the shell must be carefully measured to prevent accident. Fig. 97 *B*, however, illustrates one arrangement of a metering punch which enters the shell, forcing out an excess of water and insuring a proper amount for bulging. As shown, this is designed for a double-action press in which the blank-holding slide performs the die-closing and metering function while the punch on the crank-motion slide performs the bulging. Metering can also be accomplished with a crank-motion punch providing ample area is allowed for the rapid escape of the liquid. Entrapped air must, of course, be guarded against. Fig. 97 *B* shows shrunk rings about the lower part of the die to prevent expansion which would make it difficult to strip

the shell out of the die. Do not neglect multiplying the working pressure per square inch by the face area of the punch in selecting a press, and check the blank-holder load in the same way.

In bending hydraulically it is desirable to draw the shell with a rounded end, Fig. 96, so that it will follow the die easily. The die should be well lubricated; in fact, a light oil or soap solution lubricant may be used as the working medium.

One other method of performing bulging operations, adapted particularly to limited production, is by the use of a spinning lathe. The operation is known as inside spinning and is illustrated diagrammatically in Fig. 98. The form roll, which may be either metal or hard wood, is necessary to control the operation. The spinning roll, on an extension, as shown, is manipulated from the usual compound rest. The limit upon the amount a shell may be bulged, without annealing, is again the amount of plastic working the metal will stand without excessive hardening. This was discussed in a previous paragraph.

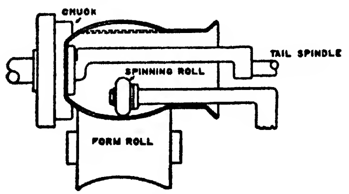


Fig. 98.—The method of performing inside spinning or bulging operations in a spinning lathe.

Beading.—The formation of ornamental or strengthening beads or ribs about the circumference of can bodies, barrel bodies and other cylindrical shapes, is possible by several methods and is rather closely related to bulging. Forming a bead is rarely, if ever, a severe enough operation to crack the metal. If the bead is high, however, it may tend to open up the side seams of pieced articles such as can bodies.

The simplest method of producing beads is to roll them in a series of beading and flanging machines. Such machines are equipped with rolls on parallel shafts, the profile of the rolls fitting the inside and outside of the desired bead as indicated in Fig. 99. A heavy spring may be incorporated in the mechanism which moves the upper shaft down, to assist the rolls over the side seams of pieced work without slipping or jumping. The rolls should ordinarily be as close to the frame of the machine as possible. On account of spring between open-end shafts, it is usually impracticable to form two uniform beads at opposite ends of a (barrel) body without additional support for the shafts. A method of providing such support is shown in Fig. 100.

Uniform pressure on the roll shafts contributes to uniform results. In this respect those machines having the motion of the upper shaft actuated by a cam (Fig. 100) have an advantage over those which are hand- or foot-controlled (Fig. 99). The cam-controlled machines

require a clutch as they make but one to three working revolutions and stop. Similar principles are used in equipment for rolling threads and knurls, operations which are related to beading.

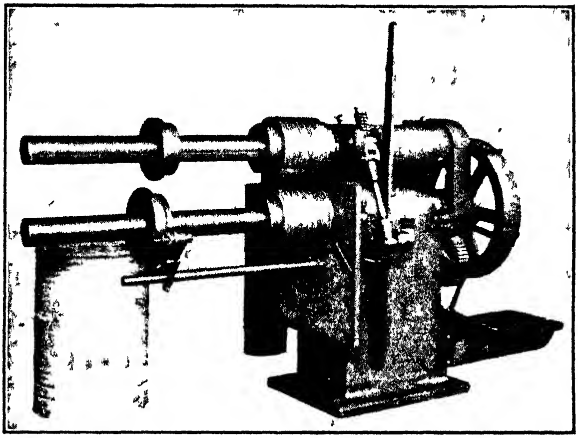


FIG 99 —A relatively large machine belonging to the hand-controlled series of beaders and flangers, equipped to bead one end of a pieced barrel while flanging the other end

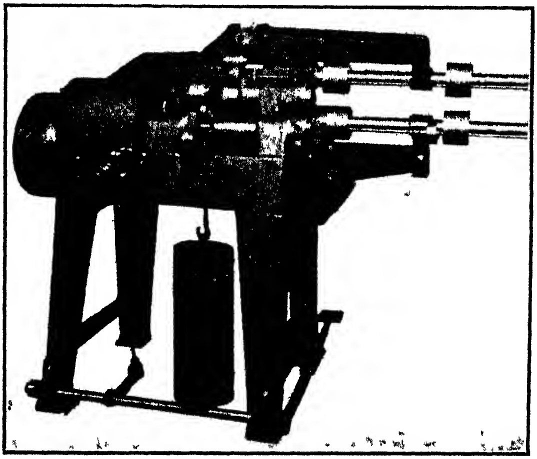


FIG 100 —The rear of a beader and flanger showing the backshaft cam which applies the working pressure, and the shaft support arrangement for two operations on a small-diameter muffler body.

Another method of forming beads is closely related to bulging in segmental dies, as shown in Fig. 93. Thus in dies, or in the beading attachments on automatic can bodymaking machines, Fig. 101, or on

the four diagonal slides on the tables of squeezer-beaders, Fig. 102, are segmental steels which expand the bead, being actuated by a wedge, cam or toggles. For holding and for sharpness of outline of the bead, there are also external contracting steels, making complete male and female dies.

Small beads in straight tubing or drawn shells may be formed in split dies by end pressure on the tube, as illustrated, for example, by

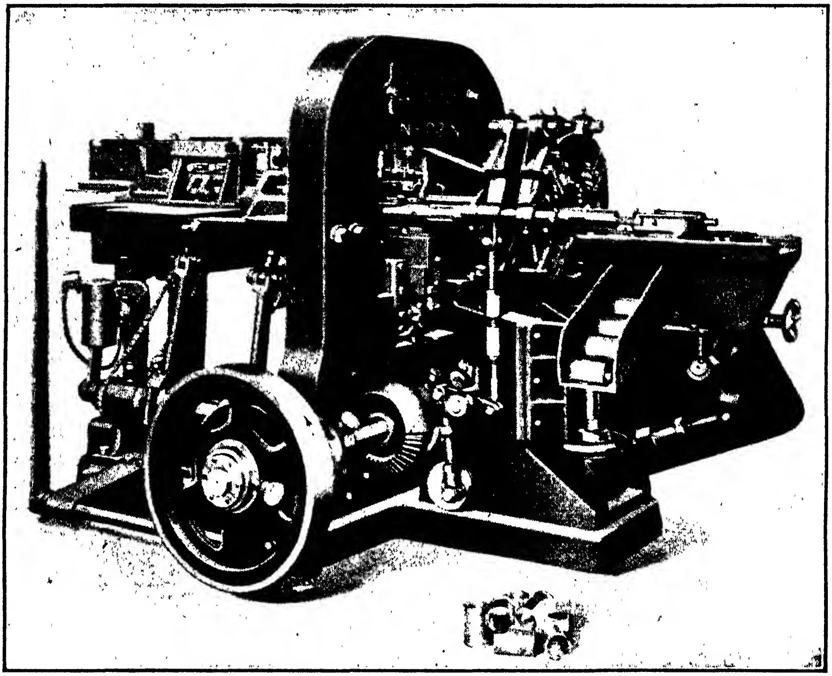


FIG. 101.—A typical cam ring closing and wedge expanding attachment on the back of an automatic can body-maker arranged to flange both ends of unsoldered bodies.

Fig. 103. It is desirable that the metal be relatively thick compared to the diameter. The bead should not be much over the metal thickness in height, or over a 90° arc, so that it will not collapse before it fills. The pressure (P lb.) required will be nearly the compressive strength of the tube:

$$P = \pi(d_1^2 - d_2^2)\frac{S}{4} \tag{9}$$

where d_1 is the outside diameter, d_2 the inside diameter, both in inches, and S in pounds per square inch is a value for the compressive strength

of the material between the elastic limit and the ultimate, approaching the latter.

Flanging.—Turning a flange out around the ends of a cylindrical or rectangular can-body is a bending operation but occurs rarely except in the can-making trade. It is preparatory to double seaming the ends on cans, tanks, barrels, etc. To form a flange the metal must be forced out against a holding tool or edge on the outside. As this is similar to the process of beading, the equipment also is similar, the tools being modified but slightly. Thus progressive flanging rolls, Fig. 104 *A*, may be used in the machines shown in Figs. 99 and 100. Care must be taken to prevent endwise shifting of the body and an uneven flange. Body-maker attachments, Fig. 101, and squeezer-flangers like Fig. 102, employ contracting and expanding die steels as illustrated at *B* in Fig.

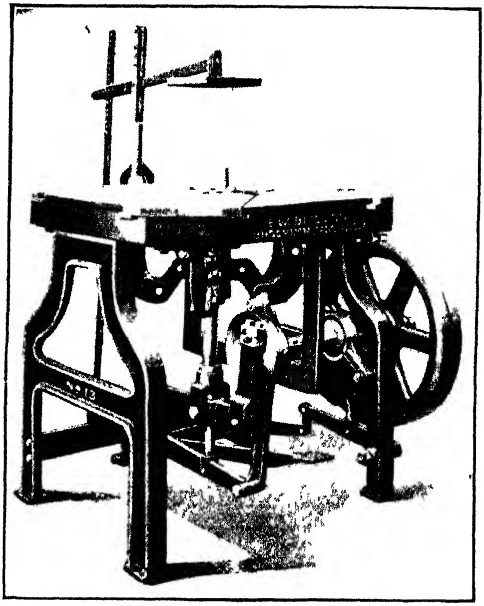


Fig. 102.—For crimping, beading or flanging operations on rectangular cans, diagonally placed slides contract or contract and expand on the table of such machines.

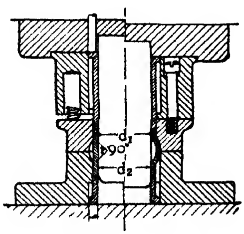


Fig. 103.—Bulging a tube by direct end thrust is limited to relatively low beads.

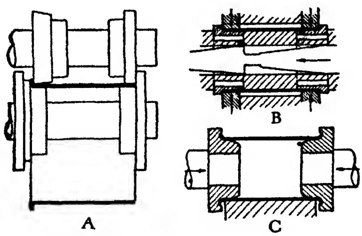


Fig. 104.—Flanges as formed (*A*) in rolls, Fig. 99; (*B*) by expansion, Fig. 101; (*C*) by end thrust, in special machines not shown.

104. High-speed double-end flangers for soldered can equipments

employ endwise die motions rather like curling, Fig. 104 *C*. The metal at the edge is stretched in increasing the circumference while flanging, so that cracks, from the edge in, would be expected from an effort to form too wide a flange (more than, say, 10 per cent of the body diameter in width).

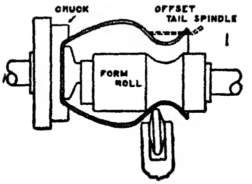


FIG. 105.—A necking operation on a spinning lathe, often a sequel to Fig 98, in that shells drawn straight are first bulged, then necked for proper contour.

Necking in.—Reducing the circumference, necking or swaging as applied to tin cans and the like employs the same range of equipment as discussed under beading and flanging, and as illustrated in Figs. 99, 100, 101 and 102. This involves making only a small offset to suit dry package slip covers, as for baking powder cans.

A necking operation, as for water pitchers, performed in a spinning lathe, is shown in Fig. 105. The tail spindle of the lathe carrying the inside chuck or form roll is necessarily offset relative to the live spindle to allow for its removal. Consequently spinning lathes for this service must be furnished with an adjustable offset tail stock.

Necking or swaging applied, for example, to tapering the ends of tubes, may be accomplished in rotatory swaging machines. The action here depends upon a series of quick hammer blows applied to the out-

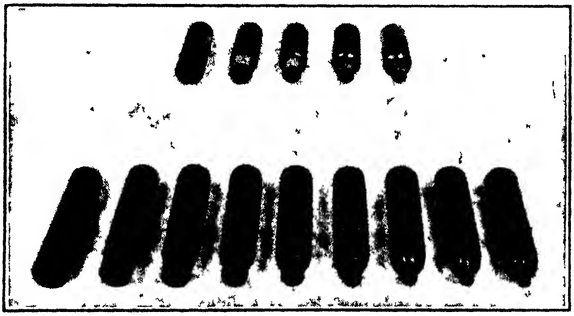


FIG. 106.—A piece of tube (above), and a deep drawn shell, each necked down by a series of press operations.

side of the tube through rapidly revolving rollers. As the number of the blows may be of the order of 8000 per minute, the individual blow is small. Annealing for extreme reductions is required as in the next case.

Necking or reducing the tops of drawn shells in the manufacture of seamless metal bottles or capsules is more nearly related to single-action redrawing. Fig. 106, at the right, shows the series of operations

in forming the bottle. The metal is stressed entirely in compression, however, instead of partly in compression and partly in tension as in drawing. For this reason the reduction in diameter per operation is somewhat lower. The eight reductions shown in Fig. 106 range from 8 per cent of the previous diameter up to 17 per cent, and this seems fairly representative of present practice. That is, if d_1 is an original diameter and d_2 is the final diameter after a proposed reducing operation, then the possible reduction is $d_2 = 0.92d_1$ if the metal is rather hard, up to $d_2 = 0.83d_1$ if the metal is soft and ductile. As such an operation involves severe cold-working and grain shattering with resultant strain-hardening, fairly frequent annealing is required for most metals, to prevent cracking and to keep them workable. For steel, of course, the higher the carbon content is, the more frequent must be the annealings, and at that the limit is around 0.20 C. Local annealing may be desirable to prevent undue softening of unstrained portions with accompanying tendency to buckle.

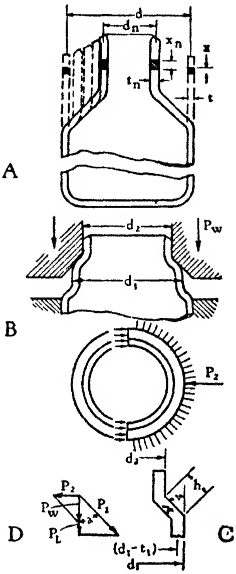


FIG. 107.—The relation of necking operations and of the forces entering into the analysis.

Fig. 107 A is drawn to compare the cross-sections of a shell, before, during and after a series of reductions. Shaded areas near the top indicate the increases in thickness and height which take place in a unit ring in proportion to the decrease in diameter. If it is desired to predict approximately what these changes will be, instead of leaving them to the more usual resolution by trial, calculations may be based upon the facts that the metal is practically plastic and incompressible (of constant volume) in the normal range of pressures and temperatures. Note that the subscript n denotes the dimensions after the series of reductions, as indicated; and that the diameters (d) are mean diameters, equal approximately to outside diameter less thickness (t). X is any unit of height. Then:

$$t_n = t\sqrt{d/d_n} \tag{10}$$

$$X_n = X\sqrt{d/d_n} \tag{11}$$

Actually t_n is likely to be a little less, and X_n a little greater, than the values obtained, as the metal is likely to flow up a little more easily than it flows in.

Fig. 107 *B*, *C* and *D* is arranged for approximation of the forces (P) occurring in any one of the reducing operations. Letters d_1 and d_2 denote outside diameters before and after any reduction, respectively. The substitution of mean diameters would be a little more accurate.

The angle a is important, especially in drawn shells which cannot be supported inside. It should be less than, say, 45°, if possible. If it is too great there is a tendency to collapse the top of the shell, in which case the reduction per operation must be reduced to keep the vertical working pressure (P_w) less than the limiting pressure (P_L) at which cave-in would be likely. Neglecting friction we may calculate:

$$P_w = \frac{t_2 \times S_u \times (d_1 - d_2)}{\cos a} \tag{12}$$

in which S_u is a value in pounds per square inch approaching the actual ultimate (compressive) strength of the material, and

$$P_L = \pi \times t_1 \times S_e \times (d_1 - t_1) \times \cos a \tag{13}$$

in which S_e in pounds per square inch is the elastic limit of the material.

The derivation of these formulae is as follows. The limiting pressure depends upon the compressive strength (P_1) of the base circle of the conical section (107*C*). That is:

$$P_1 = \pi \times (d_1 - t_1) \times t_1 \times S_e$$

then from 107*D*,

$$P_L = P_1 \times \cos a$$

or

$$P_L = \pi \times (d_1 - t_1) \times t_1 \times S_e \times \cos a$$

The sum of the horizontal compressive forces, represented as P_2, may be taken, according to pipe formulae, as:

$$P_2 = 2t_2 \times h \times S_u$$

in which $2t_2 \times h$ represents the vertical cross-section of the conical portion on which work is being done. Then from 107*D*,

$$P_w = P_2 \times \tan a = 2t_2 \times h \times S_u \times \tan a$$

and as

$$h = \frac{(d_1 - d_2)}{2 \times \sin a},$$

$$P_w = \frac{t_2 \times S_u \times (d_1 - d_2)}{\cos a}$$

Sheared Edges.—The inherent properties of the edge of a sheet of metal, as sheared or punched, are favorable or unfavorable to some subsequent operations, and particularly to the next two to be discussed.

Figs. 21 to 24 and the accompanying analysis were devoted to the progressive action of shearing or punching. It was shown that the brightly burnished portion of the edge was drawn against the wall of the punch or die until the breaking point was reached and the fracture completed the severance. A burr may and often does form at the fractured corner.

Fig. 108 shows an inherent weakness of a sheared edge, the tendency of minute crevices in the fractured portion to spread into serious cracks under severe stress. In this illustration are shown two strips of quarter-inch boiler-plate sheared to 1 in. wide. The edges of the lower strip were left as sheared. The other strip was placed in a shaper, and both edges were finished off with a light cut.

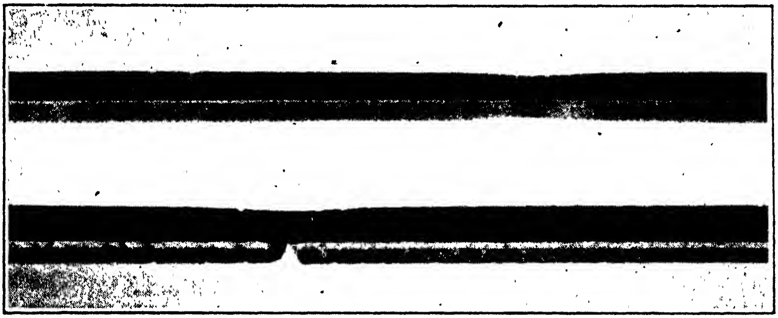


Fig. 108.—Comparative tensile tests of sheared strips, one as sheared, the other with fractured portion of edge removed by machining.

Both strips were then subjected to a tensile test in an Olsen testing machine, being stretched nearly to the breaking point and showing an average elongation of about 26 per cent. The specimen with the machined edge stood about 8 per cent more load than the other, necking in smoothly.

The specimen, as sheared, began to show small crevices along the burred or fractured portion of the edge some time before the end of the test. These gradually opened up, as the illustration shows, until one of them spread well across the strip, doing so before measurable necking-in had occurred. The burnished portion of the edge showed strains due to the crevices below it, but remained unbroken up to the development of the bad break.

Clearly the designer should avoid coincidence of a fractured edge and a high stress, either in a severe press-working operation or in a part liable to fatigue failure. The hazard may be reduced or avoided by taking the severest stress along the burnished portion of the edge,

as in the next two cases, or by shaving, burnishing or machining the fractured portion of the edge.

Burring.—Burring is turning out a flange around a hole (usually round though not necessarily so) in the bottom or side of a drawn article or even in a flat sheet. It is practically the reverse of the necking-in operations described in connection with Figs. 106 and 107, as the metal is stressed entirely in tension instead of entirely in compression.

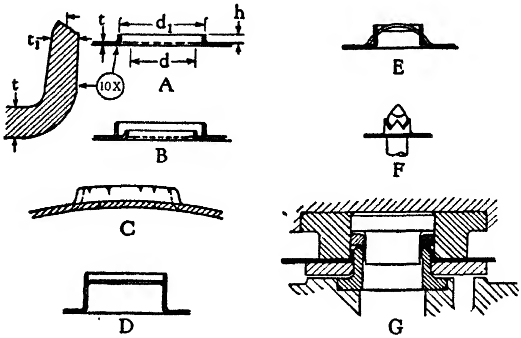


FIG. 109.—Burring or forcing out a flange around a hole may be performed in several ways according to the results desired.

In type of tools, burring resembles single-action drawing or cupping. It differs in that, instead of the side-wall material being drawn in from the outside, it is drawn out from the inside. To permit the metal to flow out, a center hole must be cut, as shown in Fig. 109, having a diameter (d) sufficiently smaller than that of the burr (d_1) to leave enough metal to form a wall of the desired height (h).

The approximation of the hole diameter, for a burr of desired diameter and height, is most easily reached by comparison of areas. Thus we may write:

$$\frac{\pi d_1^2}{4} - \pi d_1 h = \frac{\pi d^2}{4} \text{ (approx.)}$$

from which, given d_1 and h:

$$d = \sqrt{d_1^2 - 4d_1 h} \qquad (14)$$

It is best for accuracy to take d_1 as the mean diameter of the burr, that is, the outside diameter less the metal thickness or the inside diameter plus the metal thickness.

The result obtained is close enough for most requirements, though not perfectly correct on account of the corner radius and the thinning of the metal in the burr wall. This wall decreases from approximately the original metal thickness at the bottom, to appreciably less near the top, and shows considerable distortion right at the top edge. As discussed under necking in, the change in thickness is proportionate to

the change in circumference that the particular unit ring has undergone, and may be expressed:

$$t_1 = t\sqrt{d/d_1} \tag{15}$$

The limitation upon the height of the burr formed in one operation is the amount of stretching the circumference of the hole will stand without cracking. This capacity of metals is indicated, in a general way, of course, by the elongation factor in the tensile test. It is a function of ductility, best in the unworked or well-annealed state of low-carbon steel and other ductile metals. For a smooth edge in such material the increase in circumference (or diameter) should not ordinarily exceed, say, 30 per cent.

Using a proportionality factor (X) to express the relation in diameters ($Xd = d_1$), the comparison of areas formula, above, becomes:

$$h = \frac{d_1}{4}\left(1 - \frac{1}{X^2}\right)$$

or for 30 per cent stretch, where $X = 1.30$

$$h = 0.1d_1 \tag{16}$$

which may be considered the height limit for one operation.

Although our records do not show cases of raising high walls by two or more successive operations, Fig. 109 *B*, we can see no practical barrier to doing so. Local annealing of the severely worked metal around the edge will, of course, be necessary.

Referring back to Fig. 109 *A*, relatively higher burred walls may also be obtained, especially for small-diameter holes, by ironing the metal in the wall thinner as the burr is drawn up. The clearance between the burring punch and die may be as much as 30 to 40 per cent less than the original metal thickness. This will increase the burr height by approximately 40 to 65 per cent. The process is closely allied to ironing operations performed to reduce the wall thickness of drawn shells, Fig. 153.

Fig. 109 *C* merely indicates the jagged edge, due to cracks, obtained with too great a stretch in one operation. In some cases this is covered up and is not objectionable.

Fig. 109 *D* shows the combination of drawing and burring for a high wall. Metal is first drawn into a cup from the outside, then a hole is punched in the bottom and finally the burring operation throws out the remainder of the bottom. Here a relatively high side is obtained without annealing. Fig. 109 *E* shows a similar case from eyelet work

or the production of spool-ends. The drawn cup is partly opened out and partly stamped back to make the straight wall.

Fig. 109 *F* illustrates the use of a pointed burring punch, without a previously punched hole. The three or four prongs are usually flattened over in a subsequent operation to join two parts together. Combination dies, Fig. 109 *G*, are also made in some cases, to punch the center hole and burr up the sides at the same time. There are disadvantages in this practice where the metal is relatively thin, as the burring punch must serve also as blanking die, and the blanking punch must enter the die by the height of the burr, both of which conditions make for relatively high upkeep charges, especially under, say, 22 gauge.

At the left of Fig. 109 *A* is an enlarged cross-section to show the detail of the edge distortion in burring. The greatest strain clearly comes around the upper, outer edge, and it is there that cracks will start if local strains are too great. Referring back to the comments on the condition of punched or "sheared edges," note the greater resistance to cracking or greater tenacity of the burnished portion of the edge. Accordingly this burnished portion should be around the outside edge. In other words, the hole-cutting punch should enter the metal on the same side that the burr is to be formed on. If this is not possible, on account of lack of room for the die, and detrimental cracking results, the condition may be improved by reaming the punched hole, burnishing it, filing the fractured portion or possibly by punching practically without clearance if the metal is thick enough to obtain the burnishing effect in this manner.

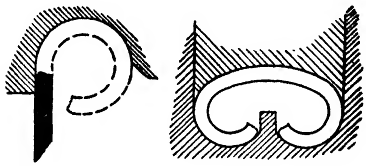


Fig. 110.—A flat strip double-curled, and a regular curl or false wire, both curling against the burnished edge of the strip with the burr on the inside of the curl.

One exception to keeping the burnished edge around the outside of the burr is found if the burr is subsequently to be curled out. Then, especially if the burr is low enough to permit doing so without cracking, the burnished edge should be around the inside edge to favor the curl.

Curling and Wiring.—In causing the edge of a piece of metal to curl around, Fig. 110, the metal is stressed both in tension and in compression but rarely so severely as to cause trouble from cracking. The object may be to protect a raw edge, to reenforce an edge (of a pail, for example), to produce a hinge or handle, to join two pieces of metal together as in double-seaming, etc.

When used for reenforcement or finish of an edge, curling is also known as *false-wiring*. And when a wire ring formed to correct diam-

eter is laid in the dies so that the metal curls around it, covering it completely and forming a strong "wired edge," the operation is called *wiring*.

Curling dies are simple in principle, though sometimes troublesome. The article must be held rigidly or at least correctly in line with the inside of the curling radius of the punch. That radius is ordinarily a plain half circle with a diameter of, say, five to ten times the metal thickness ($5t$ to $10t$). Or this may be restated: the inside radius of the curl is one and a half to four times the metal thickness A curl formed progressively by a roll must apparently be held within a smaller maximum than a curl formed in a single stroke in a die. And an inside curl must be relatively smaller than an outside curl.

The relation of the finished diameter of the curl itself to the diameter of the pail or other article or edge on which it is formed is also critical. The smallest diameter of an article on which dies are to form an outside curl might be placed at perhaps thirty times the metal thickness ($d = 30t$). All these figures are necessarily generalizations subject to modifying factors, including the condition of the metal and the skill of the die-maker.

The condition of the edge of the article or the way it strikes the curling radius is of extreme importance. In regard to the sheared end of a piece of metal, it was noted that one side or edge is slightly radiused and smoothly burnished, whereas the other edge was sharp and rough, often with burrs. In curling, *the smooth burnished edge should be against the punch radius* and the burr should be on the inside of the curl. If this is not possible the edge should be "started" or bent-in slightly, in a previous operation and in a direction to favor the curl. If one or the other is not done there is liable to be excessive wear and a tendency for the edge to jam in the radius and buckle or bend the wrong way.

Fig. 111 shows a characteristic curling or wiring die in a common type of wiring press. Owing to the comparatively short working stroke required and the relatively great height of the article in many cases, most wiring presses have short strokes and are provided with sliding die plates, as shown, so that the die may be moved out from under the punch to permit placing and removing the article. A few wiring presses are built with the so-called outside drive and extremely long strokes to permit getting the article in and out without moving the die. They are relatively slow moving, however, and inclined to be dangerous.

Fig. 112 shows a wiring die for a tapered, pieced tin pan. Note that the ring around the top of the die is mounted on springs to hold the wire ring up into the curl, a feature not required in false wiring. Note that, because of the tapered sides, the punch curling ring is made

in segments which move in as the curl is made. The grooves in the die are to clear the lock seams on the pan body.

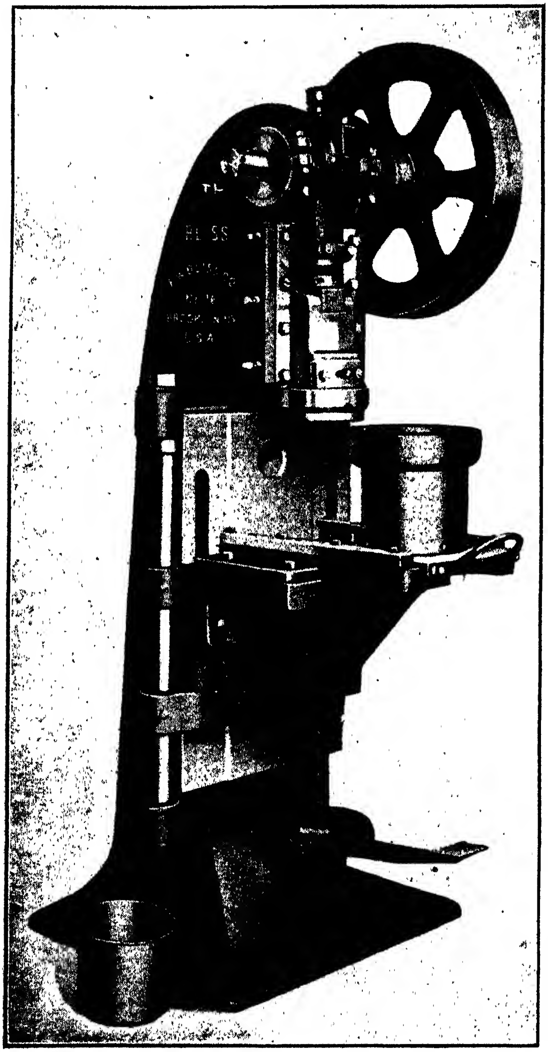


FIG. 111.—A "horning and wiring" press with a wiring die on a slide plate, permitting the curling of deep work with a short stroke.

Rectangular shapes may be, and often are, curled, though this may involve occasional difficulty from warpage in the sides, which prevents the edges from striking the curling radius properly and causes them to buckle. Straight pieces may also be curled, as in hinges where the metal is often supported closely on both sides right into the curl. Fig. 110 *B*, the cross-section of a dish-pan handle, is an example of a double curl on a straight strip. The operator places the strips the right way for curling merely by the feel of the burr. In case of trouble, the edges of such a piece might readily be "started," or bent slightly in the proper direction, by a slight angle on the sides of the blanking punch. Almost any curl can be formed in two or three steps or bending operations, as illustrated, for example, by the bushings and shovel handle, Figs. 90 and 91.

Progressive curling with rolls regularly requires several revolutions of the work relative to the roll to bring the curl in gradually. The

wider the flange is in comparison with the metal thickness, the greater are the number of revolutions required. Fig. 113 shows the relation of the roll to the work on a spinning lathe. The roll is mounted on a tilting rest so that it approaches the work in the plane of the flange to be curled.

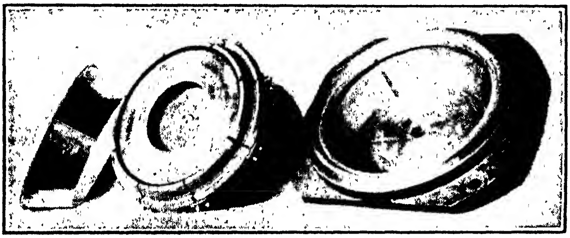


Fig. 112.—A true wiring die for a tapered pan.

Note the cutters, on the other end of the tilting rest, which prepare the edge for curling, and which are so mounted in relation to each other and to the flange that the burnished edge of the trimmed flange will be on the right side to favor curling and the burr will be on the inside of the curl.

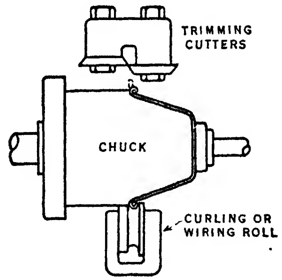


Fig. 113.—Trimming in the proper direction followed by curling as performed on a spinning lathe.

Fig. 114.—Curling-in a started edge with five rolls on an adjustable curling disc, in conjunction in this case with double seaming on the other edge.

Similarly flanged shells may be curled also in machines of the type shown in Figs. 99 and 100. Flanged screw caps and the like are curled on small fast machines which are related to these in principle. Note that flanged caps which are blanked and drawn in one operation in single-action presses, with drawing attachments under the bolster,

naturally have the edge sheared in the proper direction to favor curling.

Fig. 114 illustrates the use of sets of rolls for curling in the edges of various slip-cover cans. In almost all such cases a started edge is required to favor the curl. The rolls, mounted either in fixed position or adjustably on a " curling disc," may be mounted in automatic machines for curling only, or for trimming, beading and curling, or may be arranged on double-seaming machines for curling the top edge of the can while the bottom is being double-seamed.

The double-seaming process itself involves curling in the first operation. As shown in Fig. 115, the flanges of the can end and body must

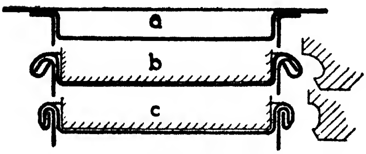


FIG. 115.—The first or curling operation and the second or closing operation in double seaming.

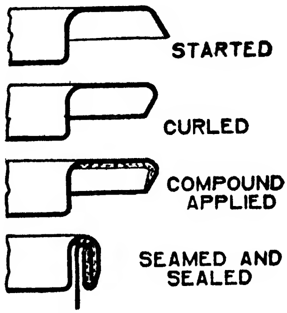


FIG. 116.—The curled, started edge on can ends for automatic stacking and feeding, and for protection of the sealing compound.

be curled together preparatory to the final flattening down. A curling roll is ordinarily used, having a groove modified from the conventional half circle as indicated. Instead of a roll, some patented automatic machines use a curling ring for the first operation, with approximately the same profile, on its inner face. The ring is larger than the can and revolves eccentrically about it, offering a better angle of incidence between the flange and curling surface than can be obtained with rolls.

Fig. 116 illustrates the " curled edge " on can ends to protect the sealing compound and to permit stacking and feeding them automatically. Such ends are drawn or stamped with a started edge and then curled between a large-diameter wheel and fixed ring or between two rolls having slightly different peripheral velocities.

Calleson dies (World Specialty Co., Merrick, L. I.) produce drawn slipcovers with curled edges. Combination blanking and drawing (with air cushion below) is completed on the down stroke. As the up stroke begins, a curling groove in the blank-holding ring co-operates with a pressure pad (approx. 750 lb. per in. of diam.) to outside-curl the edge.

CHAPTER VII

COLD-WORKING OF PLASTIC METALS

METALS must be more or less plastic to be able to undergo press-working operations. Zay Jeffries has defined plasticity as "the quality by virtue of which a substance may undergo a permanent *change in shape without rupture.*" Plastic properties vary both with temperature and with the particular metal. In cold-working, plasticity is reduced, by the operation, to an extent which depends both upon the severity of the operation or amount of cold-working, and upon the rate at which such cold-working strain-hardens the metal. The removal of the resultant strain-hardening is, or may be, accomplished by annealing or recrystallization. This restoration of the metal to its original state completes what might be referred to as "the plastic cycle."

Throughout the trade, many instances will be found in which the metal must traverse the plastic cycle several times during its fabrication. Thus, in producing an extruded cartridge case: cold-rolling to final thickness strain-hardens the metal; recrystallization (annealing) renders it plastic again; blanking and drawing the cup causes strain-hardening; recrystallization restores plasticity, extrusion (and trimming) causes severe strain-hardening; recrystallization is limited to produce semi-hard wall structure; coining the primer recess and rim strain-hardens the bottom; local recrystallization may be required. The foregoing list of operations is not complete or universal, but illustrates different operations producing essentially the same effect, and suggests the importance of strain-hardening concepts in the plastic working of metals.

Metal-working theory must always start from the internal structure and change of structure of the metal. Fig. 117 represents another effort to illustrate the atomic pattern in a group of crystals in an unstrained (annealed) metal. It represents each atom as a uniform grouping of electrons relative to a core in such a manner as to suggest the polarity which aids sufficiently hot free atoms to orient themselves in proper relation to other atoms grouped in the stronger field which their combination gives to the crystal. A number of crystals of random orientation are suggested. In any of them a number of paths at *different angles* might be selected for free slip-plane movement without serious disturbance of adjacent atoms. Again considering the whole group of crystals, it is possible to select paths at different angles across the whole mass,

which would follow free slip planes through one crystal after another without departing very much from the original direction.

Actually there are many more electrons per atom in the common metals, and many more atoms per crystal, in the usual state. Nevertheless the basic cycle remains of starting with the orderly arrangement of the annealed structure; changing the shape of the metal by many tiny slip-plane movements which gradually distort and harden the structure; and then restoring the unstrained orderly arrangement by reannealing at such temperature that the atoms are sufficiently energized to twist themselves again into unstrained relationships in their new positions.

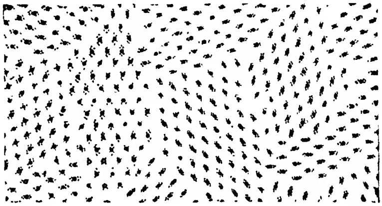


FIG. 117.—Diagrammatic illustration of atom arrangement in unworked crystals of random orientation, and of paths available for slip-plane movements. See also Figs. 9, 16 and 128.

Experiments in Strain-Hardening.—To demonstrate certain ideas regarding the changes in physical properties of plastic metals subjected to cold-working,[1] a series of experiments were performed upon a sample of Tobin bronze rod.

The recorded test curves, such as one which was shown in Fig. 15, which was the original for Fig. 118, were drawn on an Olsen recording testing machine. Tensile specimens were turned up to standard specifications with 0.505-in. body diameter. Compression specimens began approximately 0.702 in. in diameter by 0.645 in. high. Annealing was performed in an electric furnace at 1100° F. for ½ hour with cooling in the furnace. Brinell hardness numbers ranged about 132 as received, 95 annealed and 185 maximum reached in tests.

It was desired to demonstrate that the same amount of cold-working would strain-harden the same metal to the same extent, whether the metal started out in an annealed state or not and whether the work performed was tensile or compressive in nature.

In such a case a curve can be established for any given metal, at any given temperature (as normal room or shop temperature), to be known as its rate of strain-hardening curve. This curve must show

[1] E. V. Crane, "Metal Working in Power Presses," A.I.M.M.E., Feb., 1931.

the change in resistance offered by the metal to deformation, as compared with the amount of deformation. The coordinates used are laid out with pounds per square inch as a measure of resistance on one coordinate and per cent reduction in height or thickness or area on the other.

For use in comparing tensile and compressive changes the scale in Fig. 18 was shown, with explanatory notes in the discussion of "Compressive and Tensile Movement," in Chapter II.

Fig. 118 shows the first of the reworked experimental curves. The original curve, Fig. 15, as recorded by the testing machine, showed the total pressure or resistance in pounds plotted against compression in inches. Change of height in inches was easily changed to per cent reduction from the original height. But as the slug or blank was squeezed shorter its cross-section area increased, giving an unduly rapid rise to the curve. Therefore the approximate cross-section area was computed for each step by dividing the volume of the slug by its measured height. It is now felt that a truer value would be that at the mid-section or largest diameter.

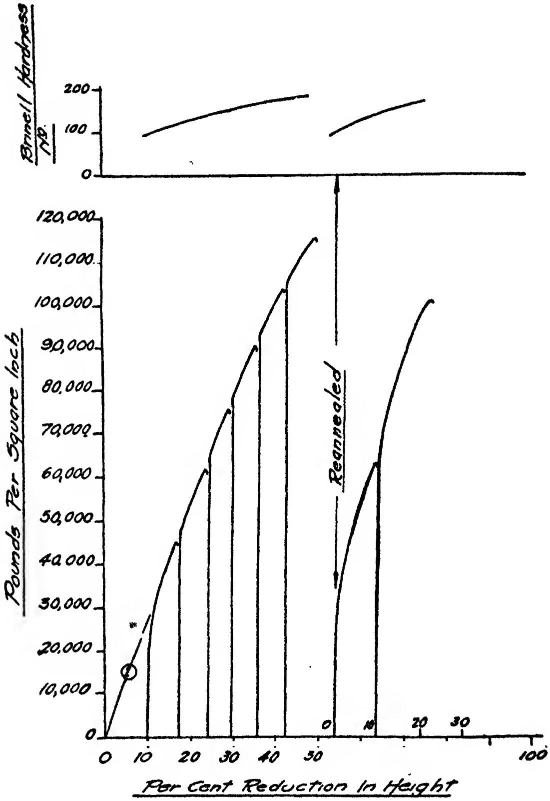


FIG. 118.—Progressively increasing yield point and rising hardness as the metal (Tobin bronze) is cold-worked in compression, then reannealed and cold-worked again (Fig. 15).

A similar process was applied to reworking or correcting the compression test curves in Fig. 119. Curves 3 and 5, as recorded, show pressures in pounds. Corrected, they show unit stress in pounds per square inch. Curve 3 was an annealed sample. Curve 5 was the

cold-drawn rod as received. Curve 3 was run continuously without interruption. Curve 1 (Fig. 118) was run intermittently, in easy stages, yet the outline of the two recorded curves (1 and 3) was almost identical.

The step-by-step test in Fig. 118 was designed particularly to illustrate the progressively increasing yield point. At each new stage of compression the stress rises elastically to the last high point. There strain-hardening is resumed, and the new test follows the outline of the plastic-working curve.

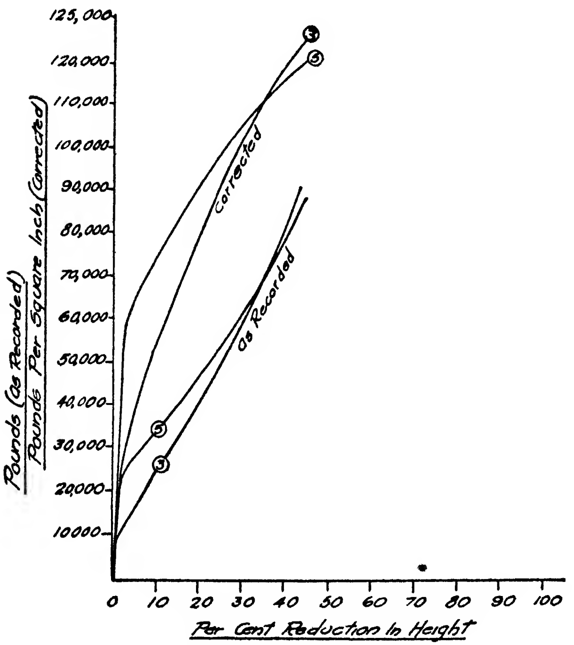


FIG. 119.—Recorded compression test curves for annealed (3), and approximately quarter-hard (5) Tobin bronze, then recalculated to show actual unit stress.

Each successive operation strain-hardened the metal farther, beyond the point where the last one left off, until the resistance offered by the metal rose to about 115,000 lb. per sq. in. This was approaching the *actual* ultimate *tensile* strength (Table I) for this material, so that internal fractures might properly be expected. Accordingly the sample was reannealed and the yield point fell again below 30,000 lb. per sq. in., indicating restoration of plasticity. The compression test was then resumed with results similar to those obtained in the first series. There was one difference, however. The plastic curve rose more steeply because the slug was now much thinner in proportion to its diameter than before. The effect of relative proportions upon compressive resistance will be discussed at some length in Chapter X.

In order to obtain an origin for the "rate of strain-hardening curve," or plastic-working curve, which would be independent of the degree of recrystallization obtained, the straight portion of the plastic-working curve (as corrected to unit stress) was continued down to the

zero yield-point line. See also Fig. 15. The per cent reduction readings were then corrected to bring this zero yield point to the origin as shown in Fig. 118.

The relation of *unit* stresses and of relative movements in opposite directions, that is in tension and compression, is of extreme importance to this argument. On the individual slip plane, recrystallization establishes an unstrained or equilibrium condition. A distortion or slip in either direction from this position might properly be expected to meet with identical resistance, so far as the individual crystal is concerned.

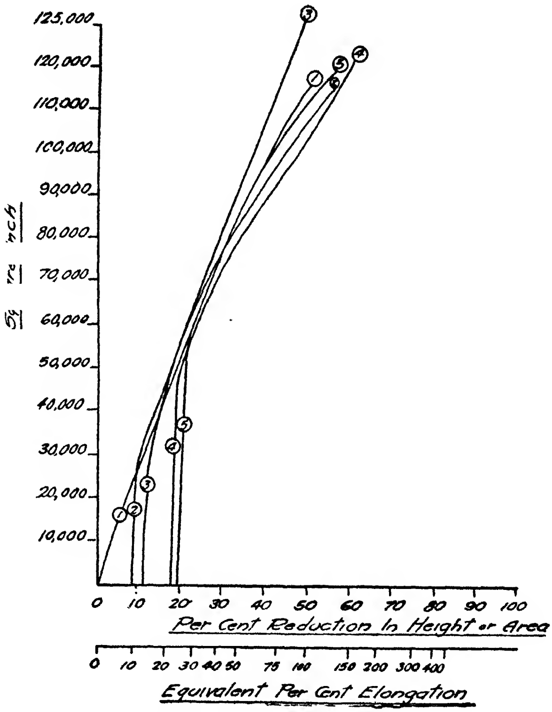


FIG. 120.—Assembly of compression and tension tests of annealed and unannealed Tobin bronze to show common rate of strain-hardening (from Figs. 118, 119 and 121).

Change in the length of a rod between 5 and 4 in. might be described either as 25 per cent elongation or 20 per cent reduction, depending upon direction. Assuming an identical uniform and unstrained structure in each case, the initial yield point, or *unit* stress to start movement in either direction, should result in a common, though higher, *unit* stress at the end of the movement. *Unit* stress, pounds per square inch, is emphasized for the obvious reason that tensile movement decreases the cross-section area and thereby tends to decrease the total stress. Similarly compressive movement increases the section area and with it the total stress. In this connection, note the difference in outlines of the "as recorded" curves in Figs. 119 and 121.

If these premises are correct, it should be possible, by using a common measurement for movement, to superimpose tensile and compressive *unit* stress curves as in Fig. 120.

As suggested by the appearance of Fig. 118, samples of the same metal, which have undergone different amounts of cold-working, should have stress-strain curves the plastic portions of which should coincide along a common "rate of strain-hardening curve." The point at which they join this curve would be more or less indicated by their initial yield point.

Accordingly, the outline of curve 1 in Fig. 118 was transferred to Fig. 120 as the basic "rate of strain-hardening curve" for Tobin

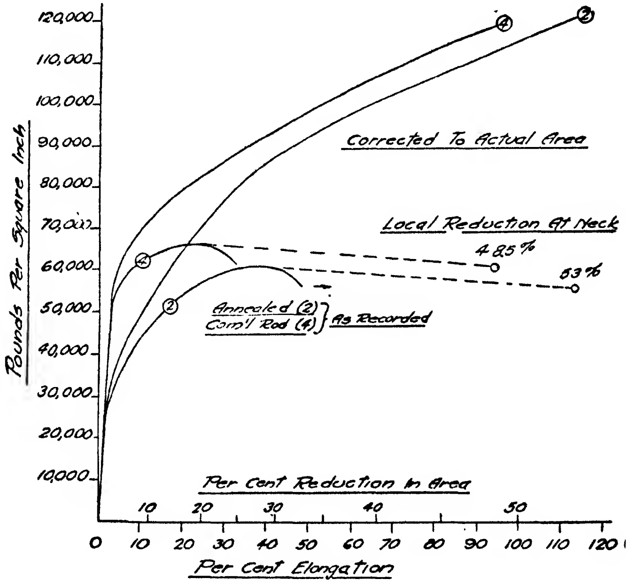


FIG. 121.—Tensile tests of Tobin bronze as received and annealed with relocation to unit stress and per cent change.

bronze (at room temperature). On this were plotted the corrected or true stress curves for the tensile and compression tests of both annealed and unannealed samples. For this purpose, the curves had to be shifted to suitable starting positions, which necessitated a correction of all "per cent reduction" readings, increasing the steepness of the curves. The resultant grouping seems reasonably close.

Inaccuracies of method may account for such discrepancy as did occur. Machine friction and play give inaccuracies in the recorded

curves which, in turn, are rarely sharply drawn lines. Vital dimensions cannot always be obtained precisely. Curves must be replotted and relocated several times with slide-rule calculations.

The tensile-test curves 2 and 4 were transferred from Fig. 121, using the unit-stress (corrected) curves with a further correction necessitated by the substitution of per cent reduction for per cent elongation (Fig. 18). The first part of these curves, up to the point where general elongation ceased and necking began, was easily corrected.[2] Curve points have since been obtained during the necking period by taking step-by-step readings of the load and the corresponding neck diameter. This portion

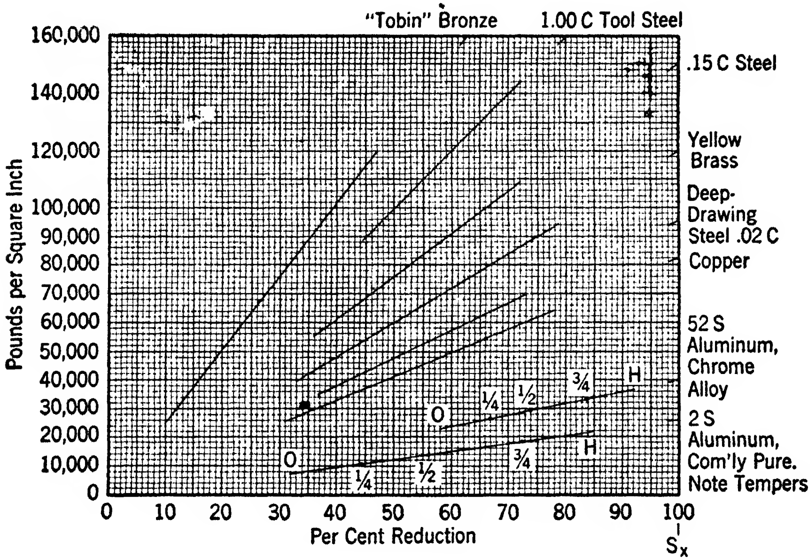


FIG. 122.—Revised tentative curves showing commercial cold-working range and rate of strain-hardening at room temperature for several metals, per Table XXVII.

of the curve was approximated, however. The final diameter at the neck and the final load locate the end of each curve.

Strain-Hardening, Rate and Limits.—With somewhat further development of technique and accumulation of data, the strain-hardening curves for a number of metals would be likely to take about the form shown in Fig. 122. These curves are designed to give a theo-

[2] See Article 29 on the relation between "Actual and Nominal Stress Intensity" in "Strength of Materials" by Arthur Morley, Longmans, Green & Co., 1928.

retical yield point for the material in any state of strain-hardness and the change in yield point which will accompany any further amount of cold-working. Each curve is limited to properties and to work performed at room temperature (say 60 to 80° F.) and to a given metal, such as commercially pure aluminum, electrolytic copper, 0.10 C steel, etc. The extent of each curve should indicate the upper and lower limits of the plastic range for the particular metal.

The lower limit of the curves should represent either normal or best commercial practice in annealing the metal. Obviously this cannot be a precisely fixed point as annealing practice varies widely. In fact, that is the reason that each strain-hardening curve is extended from a theoretical zero at the origin, as suggested by the dotted line in Fig. 123. Possibly zero is a proper value for the yield point of metal annealed to the ultimate perfection of the single crystal. Zay Jeffries [3] has commented that unexpectedly small loads will deform single crystals. Fig. 123 shows unit strengths for copper of 30,000 to 60,000 lb. per sq. in., yet according to Jeffries, "a single crystal of copper ¾ inch in diameter and long enough to grip can be bent without difficulty in the two hands." And for a single crystal of magnesium wire "the elastic limit is so low as to be hardly measurable." At the temperature of liquid air, −190° F., "it remained so soft that it could be bent with scarcely any effort."

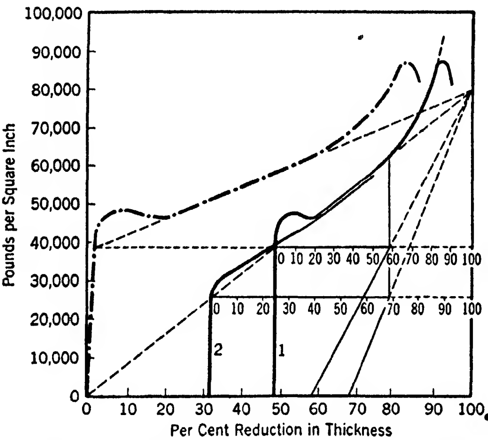


Fig. 123.—Strain-hardening curve from unrelated samples of copper showing effects of using up all slip planes and of internal fractures.

The single crystal in a piece of metal of any size is rarely realized. In commercial annealing a limited crystal size is usually desirable, as the growth of extremely large crystals is likely to take place in limited areas, under conditions of favorable strain. As a result, these local areas would be relatively softer and weaker than the remainder of the article. The subject of annealing will be discussed in some detail in Chapter IX.

The upper limit of the strain-hardening curves has been ably

[3] Zay Jeffries, "On the Plasticity of Metals," *Mechanical Engineering*, April, 1931.

described by R. L. Templin,[4] and an illustration of the phenomena which he mentions occurs at the upper end of curve 1 in Fig. 123. "When there is a marked increase in the rate of strain-hardening the explanation appears to be that most of the available crystal slip planes have been utilized and there is a preferred orientation of grains throughout the material, with the result that further working tends to make the metal brittle but at the same time causes a marked increase in tensile strength. If beyond the transition point there occurs a marked decrease in the rate of strain-hardening we usually find that the material has begun to fail by internal shear resulting not only in brittleness but also in decrease in tensile strength."

Curve 1 in Fig. 123 was arranged from a cold compression test of slugs of electrolytic copper rod, as received. The original test curve, Fig. 186, was plotted from over one hundred readings. The final slug, Fig. 187, showed marked tensile fractures around its periphery.

If curve 1 had represented a tensile test, failure would have occurred in the early part of the transition, where all available slip planes had been used up and internal fractures were starting. Thus the "upper limit" of strain-hardening curves is approximately identical with the "actual ultimate tensile" expressed as a true *unit stress*.

The initial yield point obtained in any test may show considerable eccentricity, as in curve 1, Fig. 123. Here the sharp rise above the rate of strain-hardening curve is attributed to the fact that the test was compressive in nature and was being performed upon material which had previously been cold-worked in tension. Thus it might be expected that the original material would contain many layers of atoms slightly strained or offset in one direction from the equilibrium condition. Loading in the opposite direction should then cause a reverse movement along the same slip planes. As soon as the yield point is passed the atoms would move back toward equilibrium and then beyond it, with an actual reduction in resistance before the rise begins again, as is shown in the figure. It is also common to find an initial yield point occurring below the rate of strain-hardening curve, as in the annealed material in Fig. 118.

A perfect yield point, theoretically, would be a sharp point of junction between the elastic and plastic curves. This is demonstrated (above 15 per cent reduction) in Fig. 118. There, in each successive test, the stress rises elastically to the rate of strain-hardening curve, at which point a sharp change occurs, that is, the metal yields and begins to move plastically. Elastic limit and yield point are here, clearly,

[4] R. L. Templin, "Effects of Cold Working on Physical Properties of Metals," Trans. A.I.M.E., 1929, p. 238.

the same thing. This also suggests that the plastic or strain-hardening curve might also be designated as the yield-point curve.

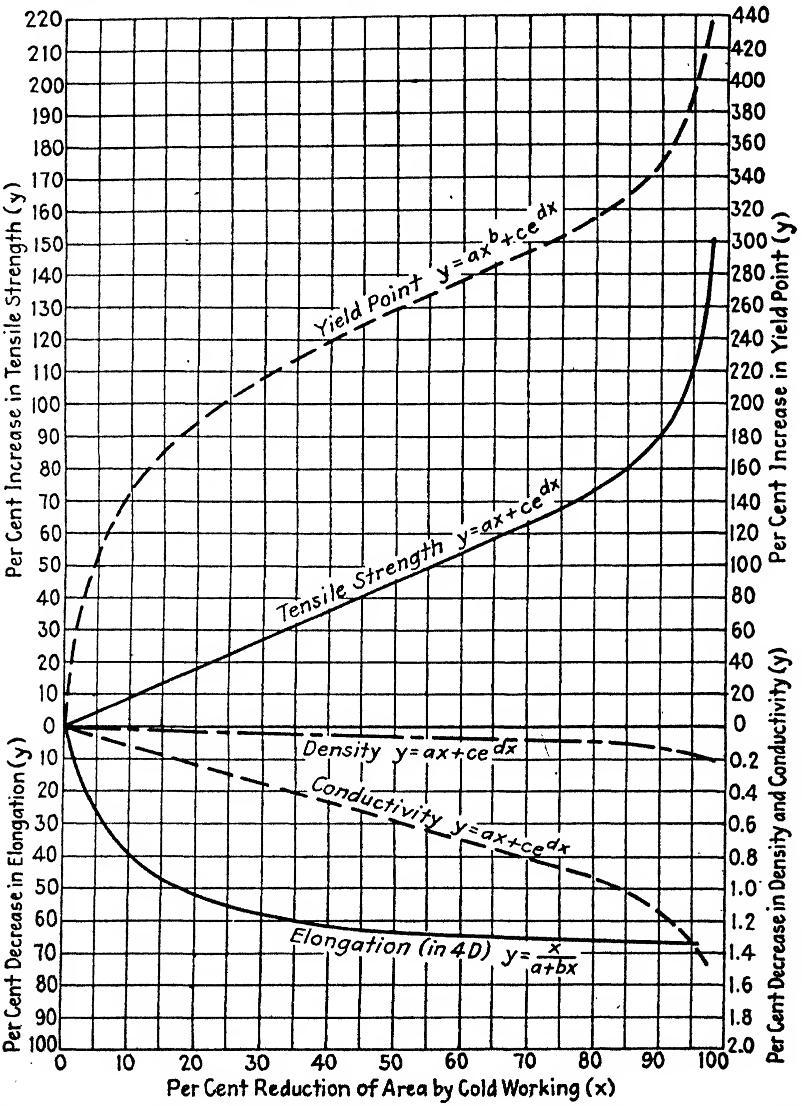


Fig. 124.—Per cent change in physical properties of aluminum due to cold-working. (*R. L. Templin.*)[4]

The straight-line form of the plastic curve, between the upper and lower limits which have been described, seems reasonably demon-

[4] *See* footnote, p. 129.

strated. An excellent illustration of it is given in Fig. 124, which is reproduced from Mr. Templin's paper on the effects of cold-working. He has there shown the changes which take place in various physical properties of aluminum as the metal is cold-worked. The curves shown are compiled from a large volume of test material.

The use of such strain-hardening curves as are shown tentatively in Fig. 122 may be illustrated by Fig. 125 and the sample shells shown in

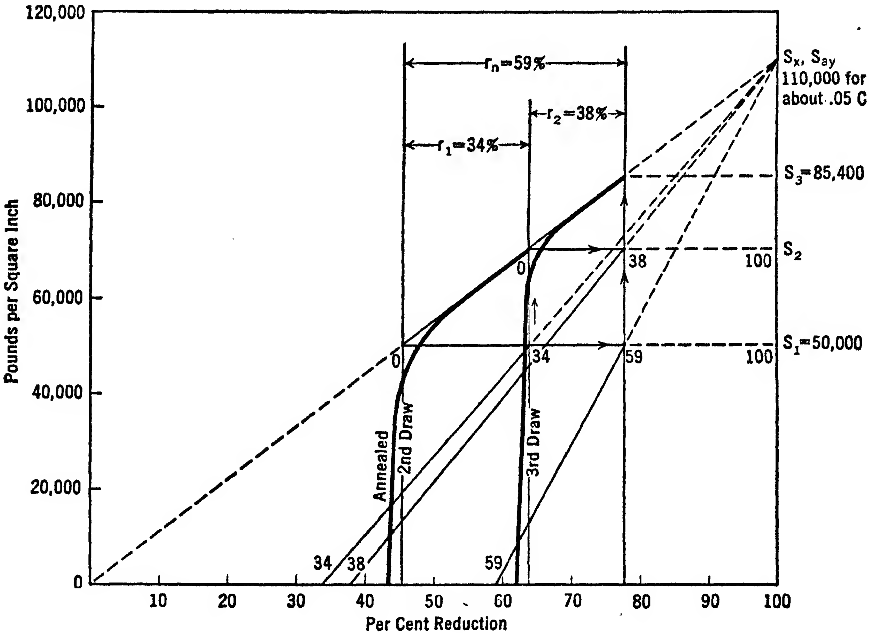


FIG. 125.—Strain-hardening during successive redraws of steel in walls of shells shown in Fig. 126 to illustrate formulae 17, 18 and 19.

Fig. 126. The first shell was blanked, drawn and annealed. It was then reduced in two drawing operations without an intermediate anneal by an amount which totals 59 per cent reduction in diameter. It is a commercial operation performed on a low-carbon deep drawing steel, cleaned before annealing, annealed in a continuous furnace and pickled thereafter.

For purposes of comparison and example the steel may be taken as S.A.E. No. 1010; carbon content, 0.05 to 0.15 per cent; elongation in 2 in., 30 to 40 per cent; reduction in area, 55 to 65 per cent; and commercial yield point, 28,000 to 36,000 lb. per sq. in., according to standard specifications.

The strain-hardening of the steel at room temperature is assumed, from rather meager present data, to lie along the line 0–110,000, Fig. 125, and between the approximate limits of 50,000 lb. per sq. in. as commercially annealed and 90,000 lb. per sq. in. ultimate. The lower limit refers of course to the theoretical yield point at the junction of the elastic and plastic curves or lines. The common test yield point would

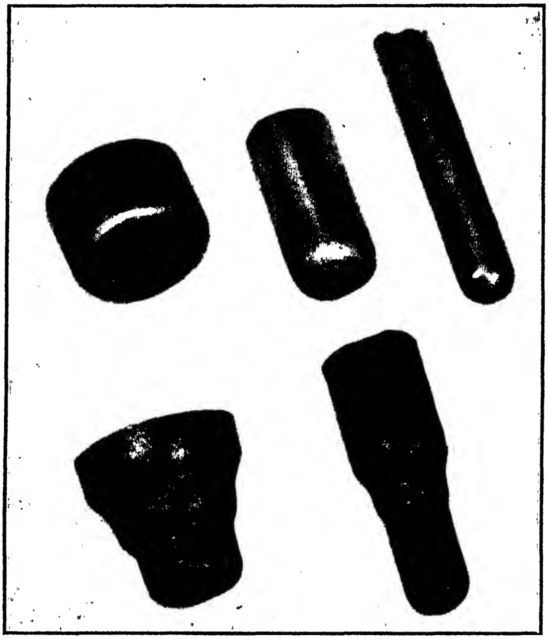


FIG. 126.—A steel shell (under 0.10 C) is blanked and drawn, then annealed, then redrawn in two steps which total a reduction of 59 per cent, which is equivalent in working to 144 per cent elongation. See Figs. 19 and 125. The two lower shells illustrate the progress of the metal through the two-step reducing dies. See Fig. 148e.

be likely to be lower than this, as given. The upper limit corresponds relatively to the 65 per cent reduction of the specifications.

For computing operations:

$$r_{1-2} = \frac{S_2 - S_1}{S_x - S_1} \text{ or } r_{1-3} = \frac{S_3 - S_1.}{S_x - S_1} \tag{17}$$

hence

$$S_2 = S_1 + r_{1-2}(S_x - S_1) \tag{18}$$

and

$$S_3 = S_1 + r_{1-3}(S_x - S_1)$$

in which

S_1 = theoretical initial yield point, pounds per square inch;

S_2 = final yield point or unit stress, not taking into account possible pyramiding of pressure in closed dies or because of relatively thin material;

S_x = theoretical extreme stress, or modulus (measure) of strain-hardening;

r = per cent reduction in the particular operation, expressed as a decimal (see also Fig. 18); also easily read by construction, Fig. 125;

r_n = overall total of a series of reductions (r_1, r_2, etc.), which is comparable with per cent reduction in the tensile test to indicate whether the series is safe without intermediate annealing.

$$r_n = 1 - [(1 - r_1) \times (1 - r_2) \times (1 - r_3)] \qquad (19)^*$$

The example illustrated by Figs. 125 and 126 may then be solved to discover the extreme unit stress, S_3, in the flange of the shell during the last reduction. The total reduction, r_n, accomplished without annealing, has been given as 59 per cent. The initial theoretical yield point, S_1, for the commercially annealed metal should be the lower limit of the strain-hardening curve. Therefore:

$$\begin{aligned} S_3 &= S_1 + r_{1-3}(S_x - S_1) \\ &= 50{,}000 + 0.59(110{,}000 - 50{,}000) \\ &= 85{,}400 \text{ lb. per sq. in.} \end{aligned}$$

This final stress is getting close to the upper limit of plasticity at which all slip planes have been used up and fractures start. In fact, micro-examination of a last-operation shell did show small fractures in the cross-section of the wall. The 59 per cent reduction in diameter (by compressive action) may be compared directly with the 55 to 65 per cent reduction in area at which a tensile fracture may be expected, according to standard specifications for this material.

The specified general elongation in 2 in. of 30 to 40 per cent is equivalent, according to Fig. 18, to a reduction in area of only 23.1 to 28.6 per cent. Such a reduction would bring the unit stress up to only 64,000 to 67,000 lb. per sq. in. in Fig. 125, so that obviously most of the plastic working is being done in the necking range of the ordinary tensile test. The 59 per cent reduction, attained in the last draws of shells shown in Fig 126, corresponds to an elongation of 144 per cent, an amount which

* Use also Chart V on p. 388 for this calculation.

is well up toward the ultimate elongation suggested in Fig. 19 for 0.10 C steel.

Table I, in Chapter II, summarizes the plastic physical properties of Tobin bronze as indicated in the experiments which have been described in this chapter. It also gives four sets of test values obtained both in tension and in compression for four points along the plastic curve for this metal, in Fig. 122. These values check reasonably closely, too, with theoretical yield points obtained by formula 19, using $S_x/1.00 = 255{,}000$.

According to the brass scale of tempers (see Table IX), a quarter-hard metal undergoes about 11 per cent reduction by cold-working from the soft or annealed state. By formula 18 and the test data available a quarter-hard Tobin bronze should have a theoretical yield point of about 50,000 lb. per sq. in. This would seem to indicate that the material listed in the second column of Table I was received in the quarter-hard state. The positions of the several tempers can be indicated upon the plastic curve of any metal in much the same manner as they are indicated on the nominal tensile curve in Fig. 127.

The value of locating the position of the tempers upon the plastic curve should be considerable in laying out further operations. Thus it will be possible to select the hardest temper which will prove satisfactory for an operation requiring a given amount of cold-working. Or the amount of work that can be performed upon metal of a given temper, before annealing is required, may be approximated.

The Plastic Cycle.—It was mentioned earlier in the chapter that metal may be required to traverse the plastic cycle a number of times in the course of its fabrication. Cold-working strain-hardens it to the limit of its plasticity. Further working would then create fractures, internal or external, which only complete remelting could remove. Annealing must therefore be resorted to, to recrystallize the structure of the metal and restore its lost plasticity in preparation for the next operation. Under most circumstances and with proper care this cycle of strain-hardening and recrystallizing may be repeated any number of times.

An excellent illustration of the plastic cycle is shown in Fig. 127.[5] Here a 67 : 33 brass, which had been strain-hardened by cold rolling to "spring" temper (approximately 60 per cent reduction), was annealed to restore its plasticity and then cold-worked by drawing to the same reduction and the same temper. Several tempers of the brass scale are

[5] Arranged from research data furnished through the courtesy of Mr. R. S. Pratt and the Bridgeport Brass Co.

indicated in their normal relation to the per cent reduction to indicate what the physical properties are in each case.

It has been mentioned that the nominal "ultimate tensile strength" is neither a true ultimate nor a unit stress. The actual ultimate unit strength would be practically unchanged throughout the cold-work range and would be much higher than the maximum nominal value. The latter is really an inverse measure of the remaining plasticity of the metal in any particular state. That is, the more the metal has been worked, the less it will change in area before all slip planes are used up

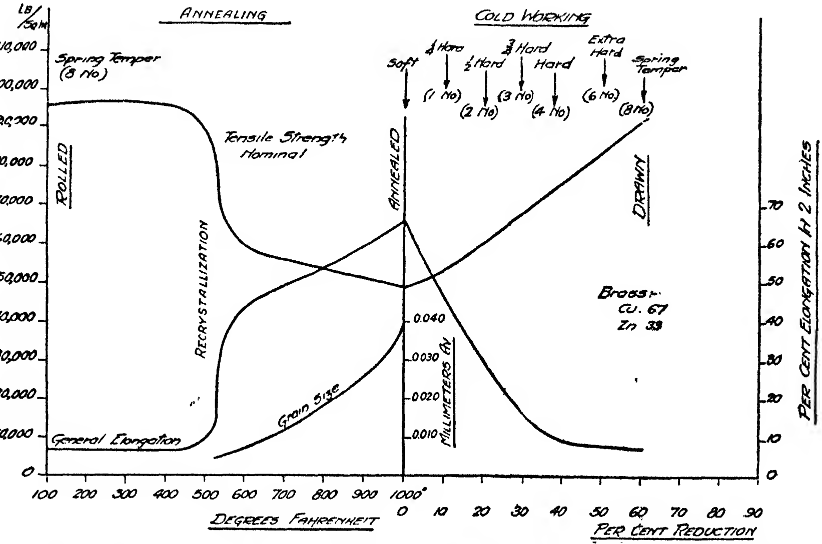


FIG. 127.—The plastic cycle. Changes in properties from spring temper through recrystallization to soft temper and then through cold-working to spring temper again. (*After R. S. Pratt*)[5]

and fracture occurs. That means a larger final area and therefore a larger total load. As this increasing load is divided by the original area (a constant), the result is an apparently increasing strength.

The cold-working, however, does increase the elastic limit, which is of interest for static designs, and also the slightly higher yield point, which is the vital figure in plastic-working.

Elastic limit and yield point would be rather difficult to measure progressively in such a test, and although they change more rapidly than the nominal tensile strength, the latter does give an idea of the way in which they change. (Note that Fig. 121 shows a comparison of nominal and actual plastic values in the tensile test. The lower curves

[5] *See* footnote, p. 134.

show actual unit stresses based upon the changing area as the metal stretches and is strain-hardened.)

Thus, in Fig. 127, exposures at the lower temperatures do not affect appreciably either the nominal tensile strength or the yield point. After an anneal at the critical temperature both drop suddenly. Annealing at temperatures beyond it causes a further gradual drop in both. Wherever this process is stopped, the yield point will have become lower than the nominal ultimate. As the material is cold-worked the theoretical yield (which may differ somewhat from the actual yield point in the lower values) will rise along a practically straight line until it joins the nominal and actual ultimate at the plastic limit if the cold-working is carried that far. In fact, however, the end of the drawing test (solid lines) is indicated at the same per cent reduction as was applied in rolling. It will be noted that the tensile strength and elongation are then the same in value as they were after rolling and prior to recrystallization.

Fig. 7 illustrated the plastic cycle for copper, except in the reverse order. That is, cold-working was shown first and annealing afterwards. The figure also showed per cent reduction in area, which is a true ultimate value and is therefore better suited to gauging plasticity than elongation in 2 in.

The Cycle and Metal Structure.—The foregoing discussion of the plastic cycle has dealt with changing physical properties, which are the outward evidences of cold-working and recrystallization. Next in order is a résumé of the effects of the cycle upon the structure of the metal itself to show more clearly why the physical properties change as they do.

A sample of any plastic metal in its cold-working range will be built up of a tremendous number of individual crystals of all shapes in random arrangement. The average size of these crystals or grains may be large or small according to the time and temperature of the last previous anneal. The internal structure of each individual crystal, in the annealed state, will be an orderly array of atoms, uniformly spaced according to the lattice pattern of the particular metal. Cold-working of the metal will cause distortion or change of shape by many slight movements in each crystal. The movements take place along the slip planes or planes of weakness between layers of atoms.

Fig. 128 shows a photomicrograph at 200 magnifications of a 70 : 30 brass which had been cold-worked to "extra hard" temper. The outlines of the old crystals can be distinguished in many places, and in each crystal are evidences of slip-plane movement along many parallel lines. This is a section of the wall of the fourth draw in the production

of a small arms cartridge case. The metal had been annealed after the previous operation to "soft temper." This would bring crystals to the size shown by the old grain outlines, but their structure would be uniform and unstrained. The 50 per cent reduction in wall thickness was accomplished by ironing, which differs from both drawing and rolling, though the effect upon the metal is substantially the same. This example is sufficiently similar to that covered by the curves in Fig. 127 so that the two may be used together to illustrate a more detailed review of the plastic cycle from the structural viewpoint. Reference should be made also to the excellent series of photomicrographs by Bassett and Davis which are shown in Chapter IX (Fig. 180) and which show the changes in grain size and condition, for substantially the same brass, from the strain-hardened state through recrystallization and grain growth to a very large-grained, unstrained structure.

FIG. 128.—Slip planes in 70 : 30 brass cold-worked by ironing to about extra-hard temper (green filter) × 200.

Starting as in Fig. 127 with the severely strained structure shown in Fig. 128, the temperature may rise to about 400° F. before any change is noticeable. The metal is alpha brass (Fig. 13), a solid solution, and the 30 or 33 per cent of zinc atoms are occupying positions in the copper space lattice. The uniformity of the original pattern has been badly distorted by the cold-working, and spacings between atoms are no longer uniform in all directions. Therefore forces between atoms are not nicely balanced as they are in the equilibrium condition, and internal strains exist.

The atom of copper has 29 negatively charged electrons moving (in a definite pattern) with relation to its positively charged nucleus. The atom of zinc has 30 similar electrons in a slightly different pattern. It is naturally a little larger and distorts the normal copper lattice to some extent, so that the brasses are less plastic than pure copper.

As more and more heat is applied the movement of the electrons becomes more violent, and the sphere of the atom and with it the whole volume of the metal increases or expands (slightly). It will be remembered that electrostatic forces of attraction and repulsion maintain such

spacings between the constituent parts of the atom group that the effective diameter of the unit is many thousand times that of the electrons which go to make it up.

When the temperature passes the critical range, as indicated in Fig. 127, the activity of the electrons is sufficient to permit the atom to rotate itself into a less strained position with respect to those surrounding it. The result is a disappearance of the old boundary lines and slip lines in Fig. 128.

With longer time at this temperature or with higher temperature the atoms tend to group themselves into larger and larger (unstrained) crystals. That is, the arrangement of the 29 electrons of the copper atom appears so to combine their forces as to produce definite directional properties. These forces cause copper atoms to arrange themselves in the face-centered cubic pattern illustrated in Fig. 9. Therefore, so long as the temperature gives them sufficient freedom, the individual atoms and smaller groups of atoms may be expected to rotate themselves into alignment with the " polarity " of the larger and stronger groups. That is grain growth.

In Fig. 127, the old grain boundaries disappeared at little over 500°. Anneals at higher temperatures produced larger grains until the 1000° anneal produced an average diameter of 0.040 mm., which corresponds to the " soft temper " rating. Had this annealing been continued at a higher temperature or for a longer time the grain size would have become much larger and the tensile strength decreased even farther. Grain growth is arbitrarily checked at soft temper, however, to avoid excessive local weakness due to over-large crystals, and to avoid an undue tendency to wrinkle which appears in drawing the large-grained metal.

It may be noted that forces between atoms are of such magnitude that we cannot normally pull them apart or push them together. Such forces, it has been shown, are very far in excess of the usual ultimate tensile or compressive strengths. The movement then is a transverse slippage in the individual crystal at an angle to the outside force, as suggested in Fig. 16.

But the metal is made up of many separate crystals of different sizes, which have their lattices or layers in many different directions depending upon the hit-or-miss growth and working of the crystal. Any continuous movement through the whole piece of metal must then find its way, through the most favorably placed slip planes, from crystal to crystal. After a relatively small movement, interference is encountered with an adjacent crystal which is differently oriented, and further slippage must take place along another plane or in another crystal.

Clearly, the larger the individual crystals, the less frequent are these

interferences and the smoother and easier is the path of any movement. Or the smaller the crystals and more frequent the boundary resistance, the harder we find the metal and the greater is its resistance to cold-working. Thus Fig. 129 illustrates the change of hardness with grain size. A second curve shows the change in grain size with temperature. These data were obtained by subjecting annealed alpha brass (68 : 32) to 50 per cent of cold-working and then testing specimens after 30-minute anneals at different temperatures. Compare it with the grain-growth period in Fig. 127.

To whatever point grain growth may have been carried, cold-working will begin to strain-harden the metal at once as indicated at the right in Fig. 127 and by the Brinell hardness curve in Fig. 118. The individual slip movement in any crystal may vary from something less than the diameter of a single atom to 5000 or more atom diameters. The action of each slip-plane movement may be merely to offset one whole section or layer of a crystal with respect to another, or it may cause a twisting or rotation of atoms or groups of atoms along the path of the movement. Its effect therefore is destruction of the continuity of the original crystal structure. In the case of severe working, Fig. 128, it may be described as shattering this structure into fragments, since the first application of heat above the critical temperature releases all strains and causes the old grain boundaries to give place to quantities of new tiny symmetrical grains (not layers of the old grain). The term fragments should not suggest tearing apart, as actual fractures cannot be cured by recrystallization, nor should they appear until cold-working has been carried so far that all available slip planes have been used up.

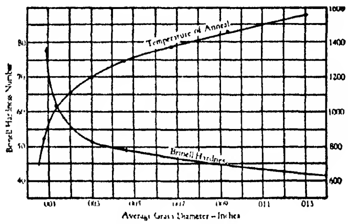


FIG. 129.—The effect of temperature upon grain size, and of grain size upon hardness. 30-minute anneals of 68 : 32 brass cold-rolled 50.9 per cent. (*After Bassett and Davis*)

The structural plastic cycle is then a case of gradually destroying continuity of the individual crystal structure through slip-plane movement, and then rebuilding new unstrained grains through recrystallization and grain growth.

Ductility Differences in Metals.—Some metals strain-harden more rapidly than others. That is, they reach a limit of endurance and require recrystallization after they have been worked by a smaller amount than others, whether the work be done in reduction or extension.

Ductility and malleability are qualitative terms ascribed to a capac-

ity to withstand considerable cold-working in tension and in compression, respectively. In the following table the order of ductility and of malleability of the several metals is as given by Jeffries and Archer, and Fulton. The differences in order between ductility and malleability are ascribed to differences in tensile, or what might be termed cohesive properties of the metals. Most cold press-working operations set up combinations of tensile and compressive stresses in the material.

TABLE XI

Order of Ductility	Order of Malleability	Type of Crystal Lattice	Atomic Number
Gold	1	Face-centered cubic	79
Silver	2	Face-centered cubic	47
Platinum	6	Face-centered cubic	78
Iron	9	Body-centered cubic [a]	26
Nickel	10	Face-centered cubic	28
Copper	3	Face-centered cubic	29
Aluminum	4	Face-centered cubic	13
Zinc	8	Hexagonal close packed	30
Tin	5	Body-centered tetragonal	50
Lead	7	Face-centered cubic	82
Magnesium	11	Hexagonal	12

[a] Face-centered cubic between 1650° F. and 2550° F. See Fig. 133a.

The metals and their alloying elements crystallize in a half dozen or more different space lattices. These are the uniform geometric patterns in which the atoms naturally arrange themselves in the individual crystals of a metal. Of these possible arrangements the "face-centered cubic lattice" is the simplest and the one lending itself most easily to cold-working as it offers the most planes of weakness or groups of slip planes at different angles to each other. Note the predominance of this pattern among the ductile metals. The body-centered cubic lattice is next, and it will be noted that iron takes a place very near the bottom in the malleability table. It may also be noted again that alpha brass, which is quite ductile and malleable, shows the face-centered cubic pattern. This pattern changes, however, as the percentage of zinc increases (beyond about 35 per cent) and at the same time much of the ductility disappears.

The lattices of zinc and tin do not lend themselves to "cold" working. But here it should be noted that the lists above are a relative grading at normal *room temperatures*, and that zinc recrystallizes at about room temperature and tin below it. Therefore these metals are

really "hot" worked. In fact, as zinc is rather close to the line it is often found desirable to apply a little heat to obtain the most satisfactory results. In this connection Fig. 130 is of interest to the trade as it indicates the variation in the ductility of zinc with temperature.

We have previously used change of hardness as an index to change of ductility. It may now be used again to indicate the effect upon the ductility of different combinations of two ductile metals which form a continuous series of "solid solution" alloys. Metals which pair up in this way usually crystallize in the same space lattice and are of not greatly different lattice dimensions. Examples are found in copper and nickel, also in silver and gold, the variation in hardness (and therefore ductility) of which was shown in Fig. 12. The increase in hardness (decrease in ductility) has been explained as due to resistance to slip-plane movement resulting from distortion of the crystal lattice by differences in atom dimensions and forces. Referring to the table it will be noted that copper and nickel differ in atomic number much less than gold and silver. From this it might be assumed that the lattice distortion would be less and the change of hardness less than that indicated in Fig. 12.

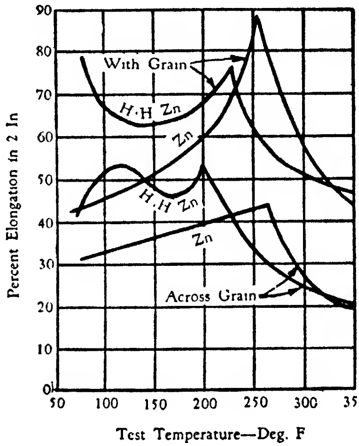


FIG. 130.—The maximum plasticity of rolled zinc lies between 200 and 300° F. as indicated by the tensile test. (*Mathewson, Trewin and Finkeldey*)

Ductile alpha brass (high brass to yellow brass), when properly homogeneous, shows only the face-centered cubic lattice of copper. The two metals are of adjacent atomic numbers (29 and 30), being therefore of relatively similar atomic volume, and the zinc is believed to occupy positions in the copper space lattice which it does without appreciable distortion or great reduction of ductility. As the proportion of zinc increases above about 36 per cent, however, beta brass begins to appear. This phase is characterized by the body-centered cubic lattice differing from that of both pure copper and pure zinc. It is materially less ductile than the alpha brasses though better adapted to hot working.

The low-carbon steels, which are of interest in the drawing group of operations, are a mechanical mixture of pure ferrite (iron), which is quite ductile, and an increasing proportion of pearlite, which is less

ductile. The pearlite contains the carbon of the steel in the form of approximately 13 per cent cementite, or iron carbide (Fe_3C), to 87 per cent ferrite. The hard and brittle cementite flakes in the pearlite break up with cold working and naturally interfere with slip movement in the pearlite crystals, increasing their resistance beyond that of the pure ferrite crystals. The variation in hardness and per cent reduction in area between substantially pure ferrite and pure pearlite are approximately straight lines, as the change is not in structure but merely in the proportions of a mixture of two unchanging structures. Fig. 19 shows these properties and indicates thereby the change in ductility of steel with carbon content, through the ferrite-pearlite range. The deep drawing and extra deep drawing steels vary generally between 0.10 C steel and nearly pure iron.

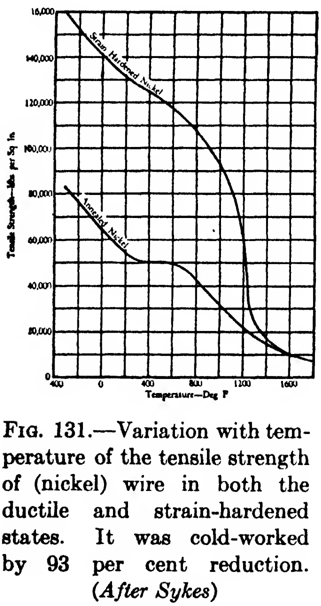


FIG. 131.—Variation with temperature of the tensile strength of (nickel) wire in both the ductile and strain-hardened states. It was cold-worked by 93 per cent reduction. (*After Sykes*)

Temperature and Plasticity. — Plasticity cannot properly be described without reference to temperature, although obviously a loose distinction between "cold" working and "hot" working is not generally applicable. More properly the term "crystoplastic" describes that plasticity possessed by many metals in their crystalline state, and the term "thermoplastic" describes the distinctly different type of plasticity found in the higher temperature range from recrystallization up to fluidity. Cumulative effects of plastic working and effects of speed of operation are different in these two groups.

Crystoplastic metals are those distinguished by the relatively simple crystal lattice patterns as discussed in connection with Table XI, and are those possessed of considerable capacity for slip-plane movement. This is accompanied by the strain-hardening which is characteristic of working in the crystalline state as discussed in the foregoing pages.

Thermoplastic working is typified in the hot forging of steels and beta brasses; the working warm of zinc and magnesium and the cold-working of tin and lead. It takes advantage of the thermally increased activity of the electrons above the crystalline temperature range and of the accompanying tendency to correct the inter-atomic strains of work-hardening as they occur, amounting to spontaneous annealing. Thus the

extent of metal movement in successive operations becomes substantially unlimited.

The boundary between crystoplastic "cold" working and thermoplastic "hot" working is therefore the critical range. This is a range of temperatures rather than a specific figure. It is the recrystallization temperature, the germination temperature of maximum grain growth, the minimum temperature of annealing to destroy the effects of cold-working. It varies with the amount of strain-hardening, being least for the most severely cold-worked material and higher for lesser degrees of cold-working. The following table, after Jeffries and Archer, gives approximately the *lowest* temperature at which recrystallization begins, for common metallic elements. These are subject, of course, to further variation in the alloys.

TABLE XII

APPROXIMATE MINIMUM TEMPERATURES OF RECRYSTALLIZATION

	Degrees Fahrenheit		Degrees Fahrenheit
Aluminum	300	Molybdenum	1600
Copper	400	Nickel	1100
Gold	400	Silver	400
Iron	850	Tin	below room temperature
Lead	below room temperature	Tungsten	2100
Magnesium	300	Zinc	room temperature

Fig. 131 shows the variation with temperature of the strength of nickel wire work-hardened by 93 per cent reduction and of annealed wire through the crystoplastic range and the joining of the two test curves as they enter the thermoplastic range. Here the effects of work-hardening disappear due to corrective thermal activity of the electrons. Compare this curve, which shows tensile strength *at the various temperatures*, with Fig. 127 which shows *room temperature* tensile values *after treatment* at the several temperatures.

Crystoplastic-working at any ordinary speeds is wholly transcrystalline. That is, deformation occurs by movement along numerous slip planes in the crystals. And "the force required to deform a crystal is practically independent of any time effect."[6] (Intercrystalline movement, cold, may occur in brittle impact, stress corrosion and fatigue.)

Thermoplastic movement may be largely intercrystalline at such low speeds as are used in testing operations. As the speed increases so does the resistance up to a point where the movement has become wholly

[6] Jeffries and Archer, "The Science of Metals," McGraw-Hill Book Co., New York, 1924.

transcrystalline. It is noted in Chapter XII, however, that, at the working speeds of normal hot-rolling and press-forging, the velocity has little or no effect on load.

An illustration of some differences in working above and below the recrystallization temperature is found in Table XIII and Fig. 132. These are taken from the interesting research work of Dr. Alan Morris.[7] It was mentioned in Table XII that tin and lead recrystallize below room temperature and zinc very little above it, so that, in the test results shown here, all three may be classed as subject to hot-working. Aluminum, on the other hand, is distinctly being cold-worked at room temperature, as its recrystallization range is much above that.

Table XIII

EFFECTS OF SPEED ON LOAD AT ROOM TEMPERATURE

Material	Reduction in Height, Blow and Squeeze, Per Cent	Calculated Resistance to Blow, Pounds per Square Inch	Resistance at Equivalent Squeeze, Pounds per Square Inch
Lead	83.0 (hot)	9,000	4,500
Tin	63.0 (hot)	16,000	7,000
Zinc	20 5 (hot)	71,000	29,000
Aluminum (52S?)	46.0 (cold)	26,500	25,500

Note: Dynamic test performed in drop hammer with 200 ft.-lb. blow. Static results obtained in a standard testing machine. After Morris.[7]

In Table XIII it will be noted that the three metals which are in their hot-working range offer about twice as much resistance to the very fast action of the drop hammer as they do to the very slow movement of the testing machine. Therefore the higher figure represents approximately the normal working load, with transcrystalline movement, of most hot-working operations. The lower figure is accounted for by a greater or less amount of intercrystalline movement according to the (slow) speed. See also Fig. 241 in Chapter XII.

The aluminum, however, is distinctly being cold-worked, so that the movement in deforming it will be transcrystalline either under slow squeeze or rapid blow. The resistance in each case should then be about the same for the same amount of deformation, and this seems to be so according to Table XIII.

In Fig. 132 are shown the curves recorded in the compression tests

[7] Alan Morris, Bridgeport Brass Co., "Plasticity of Copper-Zinc Alloys at Elevated Temperatures," Technical Publication 390, A.I.M.M.E., 1931.

used to obtain the last column data in Table XIII. It may be noted from Table XI that both aluminum and lead crystallize into the ultra plastic "face-centered cubic" pattern, and might be expected to strain-harden slowly under cold-working. The characteristic structure of the zinc crystal, on the other hand, is described as "hexagonal close packed" and that of tin as "body-centered tetragonal." Both of these are complicated arrangements of atoms which provide relatively few slip planes for plastic movement. In fact, both metals are rather brittle below their recrystallization temperatures and would strain-harden with extreme rapidity.

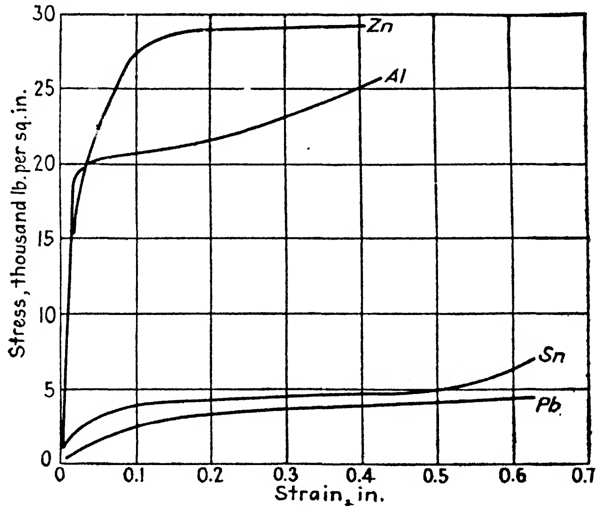


FIG. 132.—Static compression tests on lead, tin, aluminum and zinc at room temperature, corrected to unit stress. (*Morris*) [7]

The aluminum curve in Fig. 132 shows clearly the strain-hardening which accompanies cold-working. The other three show no such strain-hardening, which corroborates the fact that they are being worked "hot" rather than cold. The tin curve turns up a little toward the end, but, since the original slug was only ¾ in. high by ½ in. in diameter and has been squeezed down to about ⅛ in. in thickness, this is probably due to pyramiding pressure and surface friction.

Fig. 133 illustrates changes in the plasticity of metals in their hot-working range. The curve for machine steel shows a jump at the critical temperature (above 700° C.) where the phase change occurs

[7] See footnote, p. 144.

from ferrite and pearlite to austinite. This change is accompanied by, or is a part of, a change in crystal structure from the body-centered cubic to the face-centered cubic lattice pattern. The rise in the curve should confirm the idea that the latter is slightly the more plastic of the two structures.

In spite of the proximity of the tool-steel and machine-steel curves in this range of temperatures, there would be a very considerable difference in the cold-working range. There the high-carbon steel would be less plastic and would strain-harden much more rapidly than steel with a low carbon content owing to the larger amount of hard and brittle iron carbide (cementite) which it contains.

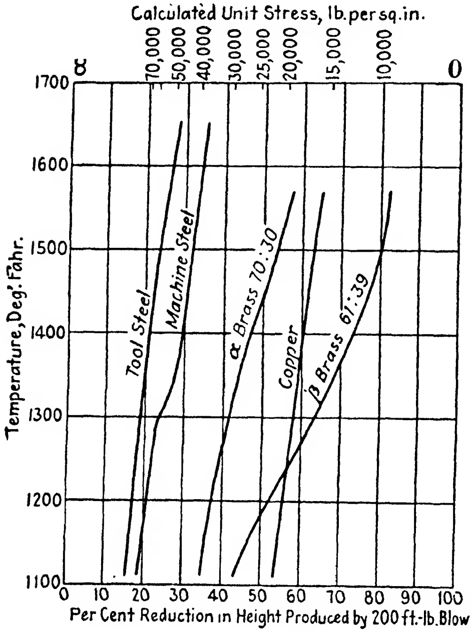


FIG. 133.—Changes in plasticity and resistance with temperature. Drop hammer test. (*Morris*)[7]

All these curves were obtained by dropping a 50-lb. hammer ram 4 ft. upon slugs ¾ in. long by ½ in. in diameter, which had been heated to the several temperatures. The calculated unit stress or resistance to this blow was computed by Dr. Morris from the energy of the hammer blow (200 ft.-lb.) and the distance in which this energy was absorbed (the reduction in height of the sample). His formula may be written:

$$S = \frac{W}{V \times \log_e(l_1/l_2)} \tag{20}$$

in which S = average unit stress, pounds per square inch;
W = work input, inch-pounds (hammer energy);
V = volume of blank, cubic inches;
l_1 = original length or height of blank, inches;
l_2 = final length or height of blank, inches.

[7] See footnote, p. 144.

This method appears to be reasonably accurate, providing the slug is not given time to cool appreciably, side flow is not restricted and reduction is not carried so far that pyramiding of pressure in the thin blank distorts the curve.

Returning to Fig. 133, the copper and brass curves are interesting in that they show again changes in ductility with changes in alloy proportions and in crystal structure. As zinc is added in solid solution with copper, it is natural that the plasticity should become less (Fig. 12). This solid solution, known as alpha brass, persists down to a copper content of about 64 per cent, and has the face-centered cubic crystal lattice. From that point on, subject to temperature, an increasing proportion of beta brass begins to appear. Beta brass has the body-centered cubic lattice which is less plastic than the face-centered cubic pattern when cold (Fig. 241). At elevated temperatures, however, beta brass becomes materially more plastic than alpha brass. In Fig. 133, the brass containing 61 per cent copper is largely alpha brass at, say, 900°. At 1500°, Fig. 13 shows that it is changed entirely to beta brass, and Fig. 133 shows, by the lower unit stress, that it is far more plastic than either alpha brass or pure copper.

Below the recrystallization range we know that changes in temperature will again affect the yield point and the rate at which it changes under plastic working. That is, referring to Fig. 122, the *rate* of strain-hardening will be reduced by an increase in temperature. Thus Templin [4] pointed out that " when commercially pure aluminum is worked at a temperature of about 200° F. the effect on the tensile strength of the metal, for instance, is only about one-half as much as when the same amount of work is done at room temperature." The same thing is illustrated in the Kent curves, Fig. 239, with respect to aluminum and, to lesser extent, brass and copper up to their recrystallization temperatures.

Under operating conditions the temperature of the metal is often raised more or less above room temperature by the plastic working involved in the particular press operation. Often, in high-speed piercing and blanking operations, sufficient heat is generated to make the piercing scrap quite warm to the touch. At times it is enough to be considered detrimental to the tools.

In the extrusion of collapsible tubes the operating speed is distinctly limited by the amount of heat generated. This same heat, however, makes possible an exceptional amount of plastic working in the extrusion of brass and copper. In the production of extruded copper radia-

[4] See footnote, p. 129.

tor tubes the metal is said to come out partially annealed instead of severely strain-hardened.

Where a consecutive series of drawing operations are performed automatically, sufficient heat is generated to keep the shells quite warm. This should reduce the rate of strain-hardening, and in fact it has often been said that the breakage was less in such a series of operations than it would be if a similarly severe series were performed slowly enough to permit the shells to cool between operations.

To what extent the rate at which metals strain-harden is reduced by relatively small increases in temperature is an interesting field for additional research. It will also be interesting to know more about the amount of heat generated in working metals plastically, and the relation if any between this and the heat delivered to the metal in effecting recrystallization.

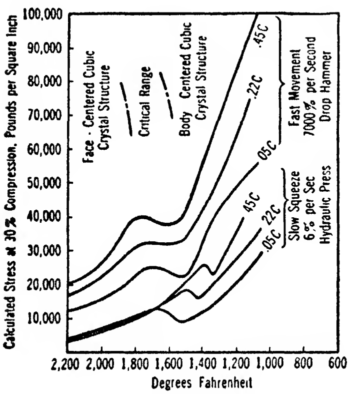


FIG. 133*a*.—Variation of stress or flow resistance with temperature in three carbon steels at high and low speeds. (*After H. Hennecke*)

Test data in Fig. 133*a* have been arranged to show effects of speed and temperature in hot-working carbon steels. Under the quick action of the drop hammer, the greater resistance to movement is attributed to lack of time for recrystallization to counteract the strain-hardening effect of transcrystalline slip-plane movement, and to less intercrystalline movement than can occur at the low speed of the static test. The curves were not carried far enough to make it obvious, but the relative effect of difference in speed is becoming less as the metal approaches the "cold-working" temperature range.

Rate and Uniformity of Plastic Working.—Another consideration affecting the strain-hardening of the plastic metals is the rate at which they are worked, or rather the extent of the work done per operation. Thus it is said that a drop hammer, in the course of a number of relatively light blows, will work the surface metal to a greater extent, whereas squeezing the final shape in the single stroke of a forging press will work the metal more thoroughly throughout. R. L. Templin [4] has said, " Products that are reduced in area 30 to 40 per cent per operation frequently exhibit differences in their mechanical properties when compared with similar products that have been reduced in area 5 to 10 per cent per operation. In general, the product that has been

worked at the higher rates has more nearly uniform mechanical properties throughout its cross-section than the product worked at the lower rates."

A similar non-uniformity of working and of consequent internal stress may result from the shape of the tools used. Thus Grimston [8] reported a careful comparison of cartridge cases reduced or ironed in conical or taper-walled dies with those produced in bell-mouthed or radiused dies. The latter were found to produce more uniform and lower internal stresses in the material with much less tendency to subsequent season cracking. Specifically he figured that the stress produced in the outer skin was 37,800 lb. per sq. in. with conical dies against only 16,000 lb. per sq. in. with bell-mouthed dies for the same reduction in wall thickness and diameter. The latter type was believed to work the metal more gradually and more uniformly throughout its section.

Investigations [9,10] of drawn wire and rod have also shown that the metal is not uniformly worked throughout its cross-section, so that, for example, there may be a materially higher stress at or near the surface than at the core. Such non-uniformity is generally blamed both upon the shape or profile of the die and the amount of reduction per pass. Thus it was noted again that small reductions tend to work the surface metal more than that further in and to set up differences in internal stresses which are not so marked in metal subject to greater and more severe reductions. And Harris [9] commented that one of the principal reasons for internal fractures at the core of drawn wire was too obtuse an angle on the draw die, or a clogged die, which in effect is the same thing.

[8] F. S. Grimston, "Influence of Die Design in the Deep Drawing of Brass," *Metal Stampings*, Oct., 1928, and the Institute of Metals, London.

[9] Frank W. Harris, "Distribution of Tensile Strength in Drawn Wire," A.I.M.M.E., Feb., 1928.

[10] Dr. R. M. Brown, "Effects of Cold Drawing on the Strength and Endurance of Mild Steel," *Rolling Mill Journal*, Sept., 1928, and Institute of Engineers and Shipbuilders, Glasgow, Scotland.

CHAPTER VIII

THE DRAWING GROUP OF PRESS OPERATIONS

THE art of working metal into thin shapes took a tremendous leap from the period of the hammer, in the hand of the expert maker of armor, to the use of drawing in the mechanical press. Of course it was not all one leap. The rolling of metal had to be developed. And the

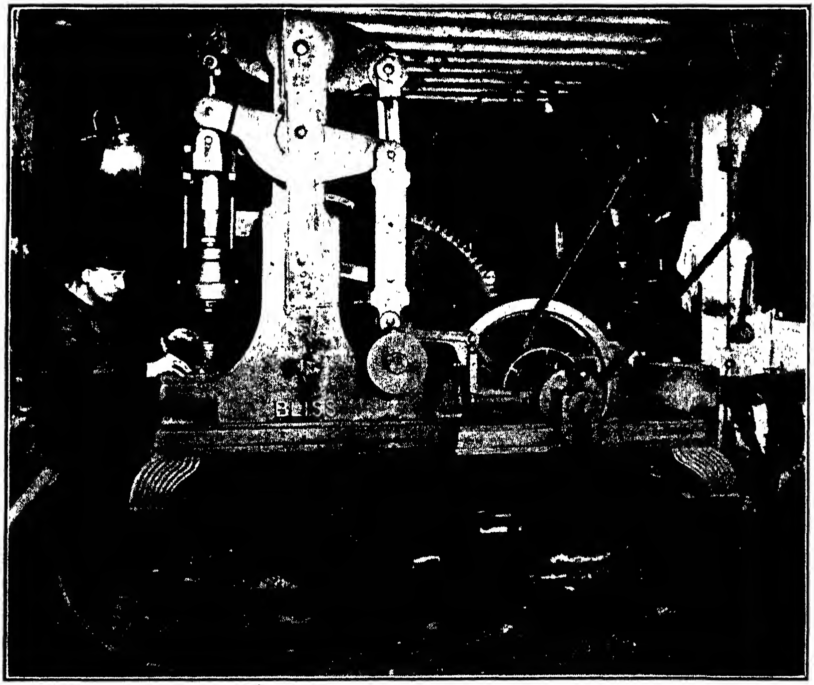


FIG. 134.—From about 1869 to 1875 or 1880 there appeared a variety of exotic cam drawing press designs of which this surviving walking-beam press was one.

mechanical hammer and spinning lathe played intermediary parts, principally for relatively small productions. An early type of mechanical drawing press, built in this country probably between 1870 and 1880, is shown in Fig. 134. Incidentally this press is still in use. The earliest

type, said to have been introduced from France in 1860, employed levers and weights for blank-holding.

The drawing group of sheet-metal-working operations includes the drawing and redrawing of all sorts of shapes, and also, because of close relationship, the ironing or thinning of side-walls in such operations. The group has much in common with the drawing of wire and some types of tube, in point of formulae and theory. Much of the explanation applies also to burring, necking and bulging operations, which for other reasons were described in Chapter VI.

The following analysis of the drawing operation will be limited, for the time being, to a consideration of round work, that is, the drawing of cylindrical shells from flat, round blanks. Redrawing or reducing the diameter of such shells follows, and then ironing or reducing the wall thickness. The drawing of rectangular, oval and odd shapes both deep and shallow involves the principles of round drawing plus plain bending and in some cases stretching only.

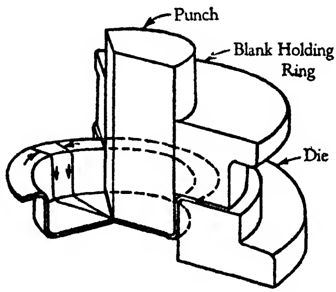


FIG. 135.—A typical drawing operation. The metal is plastically rearranged by pulling and crowding in the area between the blank-holding ring and the surface of the die.

Movement and Stresses in Drawing.—Fig. 135 shows a typical round shell partly cut away, in tools which are also cut away. The blank-holding ring, descending first, holds a plain round blank or disc upon the surface of the die ring. Then the punch descends to draw the blank into a cylindrical shell. As shown, the shell is partly drawn, and a flange of flat metal still remains between the blank-holding surfaces.

If, before starting the draw, two straight lines had been drawn upon the flat disc or blank, spreading at an angle of about 15° from its center, they would now look as indicated by the lines marked with arrows. In the bottom of the shell they are undisturbed. In the side-wall they have become parallel. And in the flange they are drawing closer and closer together as the flange is drawn in and its circumference is reduced. This change was demonstrated experimentally in Fig. 117.

The movement of the metal which these lines indicate, suggests the stresses involved. The vertical arrows denote the tensile stress or stretch in the side-wall of the shell, which is due directly to pressure of the drawing punch on the bottom of the shell. If the resistance to drawing, set up in the flange, becomes too great, the tensile stress in the

side-wall exceeds the stress at which necking occurs and the bottom tears out.

The two arrows on the flange indicate the crowding or compressive stresses set up in that area as the circumference of the blank continues to be reduced. It is this induced compressive stress in the flange which tends to cause wrinkling, and which determines the amount of the tensile stress in the side-wall. The wider the flange, the higher the tensile stress must be to move the metal. Also, the higher the compressive resistance of the metal to cold-working, the higher will be the tensile stress in the wall.

Figs. 136 and 137 illustrate the results of a group of experiments performed to explore these stresses in the wall and flange and to separate the attendant bending and frictional loads. Tools similar in prin-

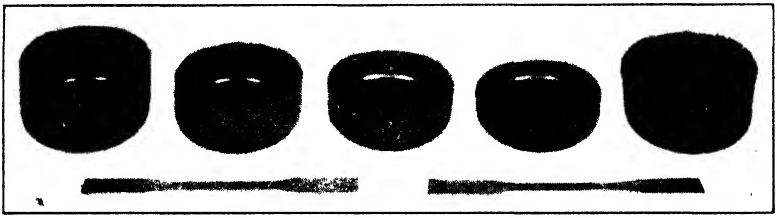


FIG. 136.—Tensile and drawing test specimens produced in exploring the stresses and changes in stresses involved in drawing to various depths and in bending and friction without drawing. Blank diameters respectively 6.5, 6, 5.5, 5 and 6.5 in. Shell diameters 3.75 in., 16-gauge deep drawing steel.

ciple to those shown in Fig. 135 were arranged in an Olsen recording testing machine in such a manner that the machine operated the punch and recorded the pressure on it. A hydraulic cylinder with pump and gauge was arranged to apply the blank-holding pressure.

Fig. 136 shows a series of four shells drawn in this manner from blanks 6½ in., 6 in., 5½ in. and 5 in. in diameter of 1/16-in. thick deep drawing steel (under 0.10 C). Another blank of 7-in. diameter tore around the bottom before the draw was completed. Finally several 6½-in. blanks were prepared with segments cut out so that there would be no drawing or crowding effect when the tools folded them into cups similar to that shown at the right. This was done to measure the bending and the friction loads separately from the total drawing load. In these tests [1] the punch diameter was 3¾ in. and the die diameter was 3 15/16 in., giving ample clearance.

The tensile tests performed on the material used showed an elastic limit of about 25,000 lb. per sq. in. and a conventional "ultimate"

[1] Tests by A. E. Caserta and W. P. Blake, E. W. Bliss Company.

tensile strength (maximum strain/original section area) of about 45,000 lb. per sq. in. Referring back to the discussion in connection with Fig. 19, the general tensile strength, before necking occurred, proved to be about 54,000 lb. per sq. in., as calculated from the actual stress and area at about 35 per cent elongation in 2 in. and about 20 per cent reduction in area. The true ultimate tensile strength after necking and at the fracture appeared to be about 95,000 lb. per sq. in. with about 65 per cent reduction in area. Certain discrepancies appear to be unavoidable in such tests of sheet material. Nevertheless, reference to Fig. 137 will show reasonably close agreement of the true "general" and "ultimate" tensile values as compared with the maximum shell wall stress and flange stresses, respectively.

In the center portion of Fig. 137 are reproduced five curves showing the variation of the drawing pressure (the tensile stress in the shell wall) as the shells were drawn. These curves are marked with the diameters of the blanks used. The scale at the left is laid out for convenience in pounds per square inch stress in the wall cross-section instead of total pressure. Under each curve is indicated the work done in drawing that shell (in inch-pounds) obtained by planimeter from the area under the curve.

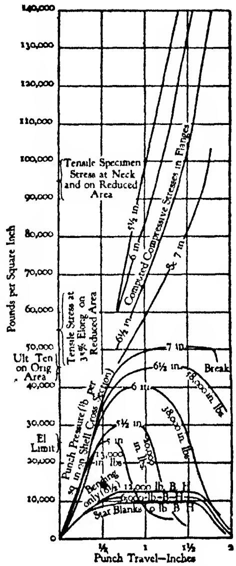


FIG. 137.—Wall stresses due to bending and blank-holding friction (star blanks), total wall stresses and flange stresses (due to drawing) as recorded and computed from test shells in Fig. 136. Note also tensile test results at left.

At the bottom is a group of three curves obtained in drawing "star" blanks into shells like that at the right in Fig. 136. The upper curve was obtained in drawing a star blank with a blank-holding pressure about equal to that used in drawing the several shells. This represents then the combined load due to bending the metal over the draw edges and due to frictional resistance to pulling out from between the blank-holding surfaces. The second curve was produced in the same way but with about half as much blank-holding pressure. The lowest curve was produced with the blank-holding surfaces blocked apart so that there was no pressure upon the blank and therefore practically no friction load. As mentioned before, there was excess clearance between the punch and die to avoid friction in that region.

The lowest curve, then, represents punch load or wall stress due to bending (over the draw edge) only. The distance from the lowest to

the second curve above, represents wall stress due to the frictional retardation by the blank-holding pressure. The distance from that curve (12,000 lb. BH) to the drawing pressure curve for the specific shell represents the wall stress required to draw, crowd or rearrange the metal in the flange against the resistance of the (circumferential) compressive strength or resistance of the material.

The topmost curves in Fig. 137 were computed from the wall stress in an effort to approximate what this compressive stress or resistance of the strain-hardened metal in the flange amounts to. The unit stresses which they show, running to and over 100,000 lb. per sq. in. for a low-carbon steel, seem high at first. It must be remembered, however, that the stress necessary to accomplish such severe cold-working or rearrangement as is taking place in the flange of a shell being drawn is necessarily high, in fact, it is ordinarily in the necking range of the tensile test. There was an excellent illustration of this in Figs. 125 and 126.

Our means of relating the compressive stresses in the flange to the tensile stresses in the wall is analogous to the formula developed for the bursting strength of thick pipe. Thus, referring to Fig. 138, let d inches represent the inside diameter of the pipe, D inches the outside diameter, S the tensile strength of the pipe material in pounds per square inch and P the internal pressure tending to burst the pipe (also in pounds per square inch). It is evident that the force required to tear a 1-in. length of pipe apart across any diameter is equal to $S(D - d)$. And it may be shown by calculus that the sum of the components of the radial bursting pressures in any one direction is equal to the product of the unit pressure and the inside diameter of the pipe $P \times d$. Equating the two to get the condition when failure occurs

$$S(D - d) = P \times d$$

or

$$P = S(D - d)/d$$

Next consider Fig. 138 as representing the relation of a blank of diameter D and a drawn shell of diameter d. The directional values of the forces are now reversed (as shown), which does not disturb the analogy. The compressive stress in the flange will be termed S_c and the resistance to reducing the diameter then becomes $S_c \times (D - d)$. The (radially effective) tensile stress in the wall of the shell is to be called S_t and the force to balance the resistance of the flange will then be $S_t \times d$. Equating the two as before,

$$S_c(D - d) = S_t d$$

or

$$S_t = S_c\left(\frac{D - d}{d}\right) = S_c\left(\frac{D}{d} - 1\right)$$

It is to be anticipated that the value of S_c will rise, with strain-hardening, from a minimum yield point for annealed material to a maximum for severely cold-worked material, after one or more draws. This rise was shown, for example, in Figs. 125 and 126. The capacity for cold-working between one anneal and the next should not be confused with the amount of drawing or reducing possible in a single operation. The two have some things in common, but the latter brings in a number of mechanical factors which will be discussed later.

Returning to Fig. 137, the upper series of curves representing values of S_c, this compressive stress in the flange, were computed for corresponding points in the middle series of curves to give some idea of the strain-hardening of the metal which was taking place in that area. S_t was taken as the total tensile stress in the wall less the stress due to bending and friction as obtained with the star shells. (A greater allowance for friction should probably be made.) A fairly satisfactory verification was obtained by drawing 6½-in. diameter blanks to several different depths, measuring the flange, correcting for corner radius and computing the stress in the flange from the drawing pressure or load as before. The shapes and general values of these curves are about as expected. The fact that the curves do not fall together or possibly in the reverse sequence may indicate that something still remains to be explained, but probably will be cleared up by refinement of the experimental equipment and methods. It seems likely that the curves originate at a common pressure but are displaced successively to the right as complete plastic motion is established later in the larger blanks.

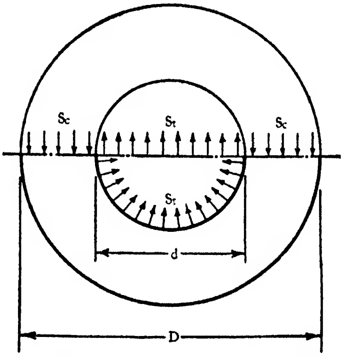


FIG. 138.—The analysis of stresses in bursting pipe applied to drawing by reversing stress directions. A balance exists between compressive resistance in the flange and resultant tensile stresses in the shell wall. D = blank diameter, d = shell diameter.

Drawing Pressure and Limits.—Clearly the working pressure, P, on a drawing punch is equal to the stress in the shell wall (plus certain frictional effects due to ironing if the clearance between the punch and die is less than the final natural thickness of the wall metal). If d represents the mean diameter of the shell wall (outside diameter minus thickness), then:

$$P = \pi d t S_t \tag{21}$$

It was found above that the unit tensile stress in the wall due (only) to working the metal in the flange was:

$$S_t = S_c\left(\frac{D}{d} - 1\right)$$

to which must be added a constant, C, to cover the corner bending and blank-holding friction. Then by substitution:

$$P = \pi\, d\, t\, S_c\left(\frac{D}{d} - 1 + C\right) \qquad (22)$$

The subscript letters t and c indicate merely whether we are dealing with the tensile stress in the shell wall or the compressive stress in the flange. That is, they indicate direction of stress.

The compressive stress in the flange begins at the yield point or the point where plastic movement starts. Thence it rises, following the rate of strain-hardening curve of the metal (Fig. 122) to a limit indicated by the amount of working or reduction necessary, or to the maximum which is possible without further annealing. This latter point is the upper limit of the strain-hardening curve.

The reduction in outside circumference due to the compressive stress in the flange is a proper measure of work done upon the metal in the process of plastic working or strain-hardening it. Expressed as a per cent reduction in circumference, this is:

$$\frac{\pi D_L - \pi D_S}{\pi D_L} \quad \text{which equals} \quad \frac{D_L - D_S}{D_L} \qquad (23)$$

since π cancels out. The latter expression is the common per cent reduction in diameter used in the charts in the Appendix, and in Fig. 125. D_L represents the larger or original diameter and D_S the smaller or final diameter. This notation is used to identify these expressions (23) with Fig. 17 and with the upper expression and scale in Fig. 18.

In this way the per cent reduction in diameter of a shell, or series of shells, may be compared directly (Fig. 18) with the per cent reduction in area (at the neck) as revealed by a tensile test of the material to be drawn. The former is a measure of the work to be done on the metal. The latter is a measure of the maximum work which can be done upon it before all available slip planes are used up and fractures begin. The plastic lower limit or starting point in both cases should be the commercial annealed state or the " as received " state. The two measures of work should be comparable to indicate the maximum reduction before annealing is essential. Thus in Figs. 125 and 126 a total reduc-

tion of 59 per cent was accomplished in steel probably a little better than S.A.E. 1010 for which the specified reduction in area is 55 to 65 per cent.

In checking up formula 22 against Fig. 137 it appears that $C = 0.3$, and the nominal " ultimate tensile strength " for S_c satisfies the maximum drawing pressures, for empirical purposes. That is:

$$P = \pi\, d\, t\, S\left(\frac{D}{d} - 0.7\right) \tag{22a}$$

It is interesting to compare, with the above formula, that of the German, Ruhrman, given in the *Iron and Steel World* of June, 1927. He gave

$$P = 2.5(D - d)\,\pi\, a\, K$$

which, reduced to the terms and form we have been using, becomes:

$$P = \pi\, d\, t\, S\left(\frac{D}{d} - 1\right) \times 1.25$$

to which he conservatively adds 20 to 100 per cent more for friction (possibly due to ironing).

The tensile stress in the wall may rise from zero (for a shell having no depth), to a maximum value, near the conventional " ultimate tensile strength," where necking occurs in tension. At this point the shell would fail by " *tearing the bottom out.*" The pressure to pull the bottom out of a shell may be obtained from formula 21

$$P = \pi\, d\, t\, S$$

where S is the nominal ultimate tensile strength. This is clearly the highest drawing pressure that can occur in any case, and is often used for purposes of approximation even though it may be more than necessary (especially for shallow draws).

The work done in a drawing operation, or the energy required to draw the shell, is represented by the area under the middle group of curves in Fig. 137 as is noted in inch-pounds. This may be approximated by the formula:

$$W = P \times h \times C \tag{24}$$

in which W is work in inch-tons;

P is drawing pressure in tons;

h is length of draw or shell height in inches;

C is a constant varying from about 0.60 for a relatively small reduction or low shell to about 0.80 for a limit draw of about 50 per cent reduction. Note, in figuring press

capacities, that this does not include any allowance for pressure drawing attachments under the press-bed, which may add a third or more to the figure given by formula 24, or for machine friction, etc.

The *theoretical maximum draw,* or reduction per operation, is approximately when $d = 0.5D$, a 50 per cent reduction. Referring to Fig. 138 and the accompanying discussion note that:

$$\frac{D}{d} - 1 = \frac{D}{0.5D} - 1 = 2 - 1 = 1$$

so that by the formula, the flange stress S_c, which always exceeds the yield point, sets up a wall stress S_t of equal amount. When the stresses due to corner bending and blank-holding friction are added to this, it is apparent that the total stress in the shell wall will be considerably above the yield point of the metal and dangerously close to the necking range as soon as the draw starts. Under such conditions the shell wall is becoming thinner and its strength is becoming less. Meanwhile the flange metal is being cold-worked in compression and is likely to be increasing in resistance faster than the flange is decreasing in width. This depends upon the rate of hardening in the working range.

FIG. 139.—Two 16-gauge stainless steel shells: one reduced about 46 per cent, cracked in standing overnight because of severe strain-hardening and surface fractures; the other reduced 48 per cent and annealed at once to prevent cracking.

Fig. 139 shows a stainless-steel shell which has undergone a 48 per cent reduction from the flat blank. It had to be annealed at once, however, to prevent cracking in standing, and the surface of the shell was badly torn. That is, many small criss-cross fractures were apparent under small magnification. These, of course, could not be removed by annealing, so that the reduction was really too great for practical purposes. It may be noted that this material is said to show 70 per cent reduction in area on test, which, according to the foregoing discussion, should mean that 70 per cent reduction in shell diameter without annealing could be obtained under ideal conditions, starting from the annealed state.

Note in Fig. 137 that the 7-in. blank which was being reduced about 47 per cent failed part way down. This was a deep drawing steel which should probably do better. Accordingly the failure may have been due

to improper annealing, too little corner radius or excessive carbon content.

Fig. 126 showed shells which had been reduced 59 per cent without annealing, though not in one operation. This indicated a steel having a relatively low rate of strain-hardening, and favorable die conditions.

In practice the *maximum first-operation draw* varies up to, say, 35 to 47 per cent reduction. This depends also upon the blank-holding conditions, which in turn depend largely upon the relation of blank diameter to thickness.

Blank-Holding (Round Blanks).—In straight-walled round shells, the (sole) object of a blank-holder is to prevent wrinkles forming in the flange, as their formation interferes with, or prevents, the compressive action which rearranges the metal from flange to side-wall. For such shells the required pressure varies from zero to a maximum as the tendency to wrinkle varies with the proportions of the shell. In the case of tapered walls, where the metal is out of positive control and the tendency to wrinkle is thereby increased, the blank-holding pressure may have to be increased in an effort to hold the metal flat to the punch. In drawing very shallow shapes the compressive action and tendency to form wrinkles is negligible, but a high blank-holding pressure is required in order to hold the flange and stretch the body of the metal beyond the elastic limit so that it will retain its shape (Fig. 142).

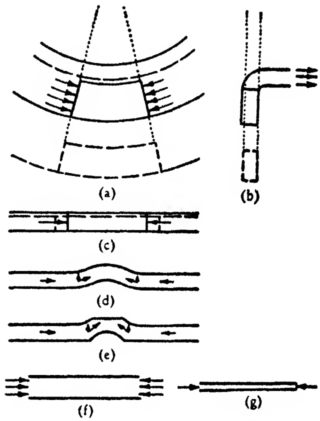


Fig. 140.—Rearrangement of same volume of metal (dotted to solid positions) in a shell flange (*a*, *b*, *c*); wrinkle formation and up thrust (*c*, *d*, *e*); advantage of relatively thick material in resisting buckling (*f*, *g*).

Fig. 140 is arranged in an effort to explain the formation of wrinkles in the flange as a shell is being drawn. Two positions of the same volume or section of metal are shown in plan at (*a*), in section at (*b*) and in edge view of the flange at (*c*). The dotted lines indicate the original position at the start of the draw; the solid lines show the position with the draw approaching completion. The arrows indicate the high compressive stresses which must be developed in the flange to compress the metal into the progressively smaller circumferences. (See also Figs. 16, 135 and 137.)

The condition at (*c*) may be compared with that in a structural column which is loaded beyond its elastic limit and is gradually being

squeezed down plastically. If the column is thick and short as at (*f*) it may become shorter and thicker without buckling. That condition is paralleled by those brake drums and first-operation hubs, etc., where the metal is so thick relative to the diameter and depth of the shell that no blank-holding pressure is required. On the other hand, if the column is long and thin as at (*g*) it will undoubtedly buckle and bend to one side under the load, though the load per unit of area is no greater than in the previous instance. This case parallels those relatively thin blanks which must be held flat to prevent buckling under the compressive stresses.

The initial buckle or wrinkle is due to some lack of uniformity in the movement or resistance to movement in the cross-section of the metal. As shown in Fig. 16, the plastic movement in the individual crystal is by angular slippage. It may, therefore, be seen that a large crystal or a group of crystals, of especially favorable orientation, may

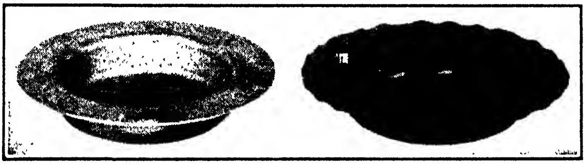


Fig. 141.—Formation of wrinkles in a shell flange due to insufficient blank-holding pressure. Such wrinkles can be prevented with sufficient pressure, but cannot be removed once they are started.

reduce the resistance locally on one surface of a blank or one side of a column and tend to cause a buckle or wrinkle toward the other side. A blank-holder pressure sufficient to resist or compensate for this non-uniform movement would prevent the buckle. Once a wrinkle starts, the perpendicular component of the compressive stress increases rapidly as shown at (*d*) and (*e*). Also the growth of one wrinkle raises the blank-holder from the surface of the metal so that others can form easily. Fig. 141 illustrates the tendency of wrinkles to space themselves fairly uniformly in uniformly stressed material.

The pressure to hold the blank flat during cylindrical drawing varies from nothing, in the case of relatively thick blanks, to a maximum of about a third of the drawing load. This figure seems to be quite generally accepted in this country and to be reasonably well borne out by experimental results and data obtained by the use of pneumatic draw cushions. Ruhrman's formulae apparently develop to 1.25 and 1.5 times the drawing load, for the blank-holding pressure, but this seems high except for conical or tapered work. For the same shell

diameter and thickness, reducing the height of the required wall reduces the drawing load and reduces the blank-holding pressure even more rapidly. The stretching of shallow vault tops and many automobile body sections is in a different class, for, as illustrated in Fig. 142, the vertical component of the elastic limit of the metal may be comparatively small, whereas the blank-holding pressure required to hold the metal from slipping is likely to equal or exceed the drawing pressure. Of course, draw beads or mouldings may be used on the blank-holding surfaces to retard the metal without using so much pressure.

Single-action drawing or cupping (without using blank-holding members), Fig. 143, is practical where the metal thickness is sufficient in proportion to the blank diameter and amount of reduction to offset the

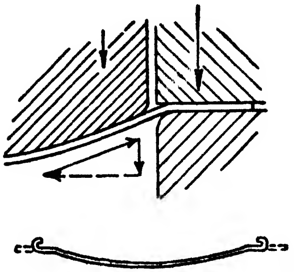


Fig. 142.— A relatively low drawing pressure but high blank-holding pressure is required in stretching a shallow shape.

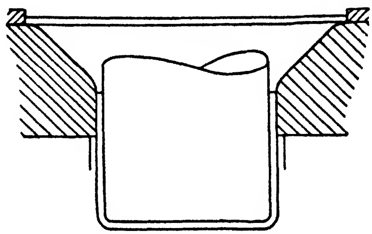


Fig. 143.—Single-action drawing, without a blank-holder, of a blank which is thick enough relative to its diameter to preclude wrinkling.

tendency to form wrinkles. Table XIV, p. 163, and the chart, Fig. 421, p. 467, are prepared from such data as is available to indicate approximate limits. Easier flow and less frictional resistance reduces the drawing load materially below that given by formulae 21 and 22. As described in the third paragraph, p. 175, severe ironing may follow the cupping in the same die.

Shell and Blank Dimensions.[2]—The most commonly used method of computing the proper blank diameter for a desired shell is by comparison of surface area. Thus, for a plain cylindrical shell, if d equals the shell diameter, h the shell height and D the blank diameter, then area of the blank, $\pi D^2/4$, is equal to the area of the shell wall, πdh, plus the area of its bottom, $\pi d^2/4$, which reduces to:

$$D = \sqrt{d^2 + 4dh} \tag{25}$$

[2] Especially for shells having complicated and ornate profiles, a method of obtaining blank diameters by construction is given by F. D. Jones, "Die Design and Diemaking Practice," Chapter II, the Industrial Press, 1930.

This value is not accurate; it is somewhat high because it does not consider the bottom corner radius, the metal thickness or changes in thickness in drawing. The thinning of the metal in the radius and lower wall and thickening in the upper wall make accurate figuring very difficult. Accordingly, common practice is to make the drawing dies first, cut various trial blanks by hand and try them out to obtain the proper blank, before the cutting edges are finished. The above formula is then sufficiently accurate to approximate the first trial blank.

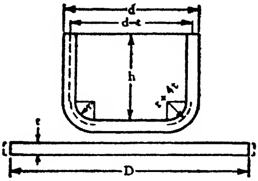


FIG. 144.—Cross-section of shell and blank showing essential dimensions for computations.

If the metal is thick relative to the diameter of the shell, it becomes desirable to use the mean diameter of the shell for d, as shown in Fig. 144. This is the outside diameter of the shell less the average wall thickness of the shell.

If the corner radius is considerable, the area of the metal there may be computed separately from that in the shell wall and bottom, as indicated in Fig. 144. This corner surface may be approximated as: area $= \pi^2 r(d - 0.728r)/2$, in which r is the corner radius. The blank diameter then becomes:

$$D = \sqrt{(d - 2r)^2 + 4d(h - r) + 2\pi r(d - 0.7r)} \qquad (26)$$

If the metal thickness is to be considered as in Figs. 129 and 130, this becomes approximately:

$$D = \sqrt{(d-2r-2t)^2+4(d-t)(h-r)+2\pi(r+.4t)(d-.7r-.3t)} \qquad (27)$$

in which d is outside shell diameter, r is inside corner radius and h is inside height. In this the mean corner radius has been taken as $r + 0.4t$ in accordance with the discussion in connection with Fig. 79 *A*.

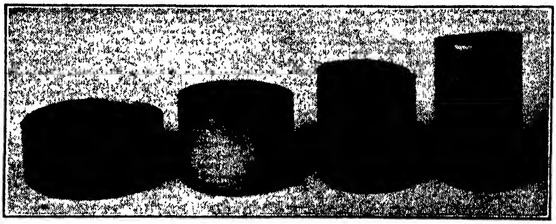


FIG. 145.—A typical series of shells in light-gauge steel, the first blanked and drawn in double-action dies with a 40 per cent reduction. The rest reduced single action by 18, 14.6 and 10.3 per cent respectively, with their metal-thickness-to-diameter ratio ranging around 2 per cent.

In the above formulae there is no allowance for extra height required to compensate for high and low spots or "ears" around the top of the drawn shell. Such "ears" are well known to the shop man and are

variously attributed to unevenness in holding pressure pins, unevennesses of die surfaces or clearances and directional non-uniformity of material, resulting from direction of rolling, which has not been completely removed in recrystallization. There seems to be justification for all these reasons, but under favorable conditions shells can be produced which are fairly square, as in Fig. 145.

The above formulae do not take into account natural wall thinning near the bottom and thickening near the top nor enforced reduction in thickness by ironing. Close approximation in such cases requires figuring by volume instead of by area. Fig. 146 shows in section a cartridge case and the blank for it. This is an extreme case in which the ironing is severe and the wall thickness is not uniform. Here the blank is approximated by volume or by weight.

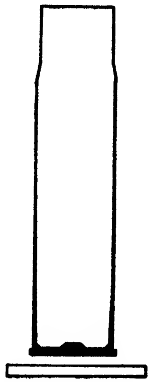


Fig. 146.—Cartridge cases are produced by severe ironing so that the blank can be computed only by weight or volume.

The following comparative table is prepared from formula 25 (which neglects thickness and corner radius) to show the relative shell height obtained with various reductions. The minimum blank thicknesses for single-action (S. A.) and double-action (D. A.) draws are values offered tentatively in accordance with the discussion of relative thickness and diameter.

Table XIV

RELATIONS OF BLANK AND SHELL DIMENSIONS

Per Cent Reduction in First Draw $\frac{(D-d)}{D}$	Shell Height, Per Cent of Its Diameter $\frac{h}{d}$		Probable Minimum Blank Thickness, in Per Cent of Its Diameter[a] $\frac{t}{D}$ (D.A.)	(S.A.)
30.0	26		0.15	(?)
35.0	34		0.2	1.5
40.0	44	−0 +?	0.3	
45.0	58		0.4	2.0
47.5	65		0.5	2.5

[a] See also a nomogram, Fig. 421, in the Appendix, presenting similar data.

It will be noted in the table that the maximum first-draw wall height is 65 per cent of the shell diameter. Yet instances are not

infrequent of one-draw shells whose height exceeds their diameter. There are two possible explanations. One is that the rate of strain hardening is so low that the blank may be reduced over 50 per cent without serious wall thinning. The other is that the material is relatively thick, the bottom corner radius is relatively large and there may be ironing of the wall, all of which increase the relative height for any given reduction.

Reducing or Redrawing.—Fig. 147 is a fairly typical series of shells produced in reducing or redrawing operations. The lowest shell was blanked and drawn in a combination die. This was a double-action operation (with blank-holder) accomplishing about a 44 per cent reduction from the flat blank. The first redraw, also double action, reduced the diameter about 29 per cent. The remaining four redraws were all performed single action and averaged about 24 per cent reduction each with small variations above and below that figure.

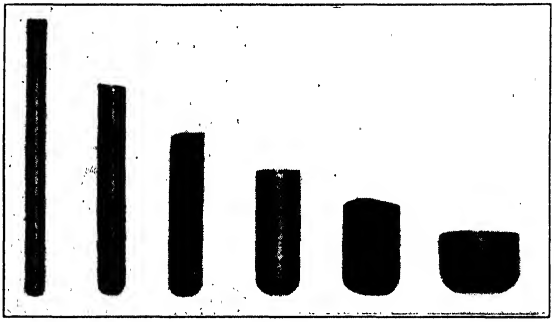


Fig. 147.—A series of reductions in brass to which the descending rate was not applied. First draw, double action, about 44 per cent reduction. Subsequent reductions 29, 23, 24, 21, 27 per cent respectively.

Fig. 145 showed a series of relatively thinner shells with more conservatively chosen operations. The first draw effected a 40 per cent reduction from the blank, and the redraws reduced the diameters, respectively, 18, 14.5 and 10 per cent.

It has been stated from practice that, in double-action redrawing, the successive reductions may run up to 30, 25, 16, 13 per cent, etc. If the metal is relatively thin the series should start lower. That is, if its thickness is in the nature of 0.2 or 0.3 per cent of the blank diameter, the first redraw should not exceed 25 per cent, for example.

In single-action redrawing (without a blank-holder), beginning perhaps with a metal thickness of 2 or 3 per cent of the blank diameter, the successive reductions may be 25, 20, 16, 13, 10 per cent, etc. If the metal is somewhat thinner the series should start, say, at 20 per cent. Logically these reductions seem low, and single-action reductions have been recorded which are greater than normal maximum double-action reductions.

There is also a limit to the greatest thickness of metal that can be redrawn in double-action dies. For small reductions of small shells, the blank-holding ring necessarily becomes rather thin. If, in such a case, the shell wall is so thick as to equal or exceed, say, half of the ring thickness, it may be anticipated that the end of the ring will gradually close in and eventually seize on the drawing punch.

In Fig. 148 *A* is illustrated a typical double-action redrawing die with the shell partly drawn through. The shell of the preceding operation is indicated in dotted lines. It may be seen that the redrawing operation is similar, in the action of the metal, to the first-operation draw shown in Fig. 135, except that the first-operation shell wall acts as a feeder to replenish the metal in the flange, and that there is added to the load on the punch the bending and frictional resistance of pulling the metal over the outside edge of the blank-holding ring.

It is this added bending and friction load which makes it impossible to take as large a reduction on a redraw as on a first draw. The decreasing amount of reduction on subsequent redraws, indicated above, can be explained only as an allowance to compensate for the increased (strain) hardness of the metal. Annealing would then permit starting again at the maximum reduction. Practice is not in entire agreement on the descending series of reductions as evidenced by Fig. 147, in which the *single-action reductions are uniformly about 25 per cent.* Note that, as the reductions progress, the ratio of thickness to outside diameter increases, favoring larger reductions. In fact, the author can see no theoretical reason, at present, why some single-action and double-action reductions should not materially exceed 30 per cent.

Chart V in the Appendix may be conveniently used in arriving at the number of operations to produce a round shell, and in proportioning the reduction per step. By using the blank diameter and final shell diameter the total per cent reduction may be obtained to judge of the need of annealing, if strain-hardening data on the metal are available. It should be remembered that a limit draw or reduction is likely to necessitate considerable care in finishing the tools for satisfactory results.

It is evident that this chart may also be used conveniently in planning the use of stock draw rings on a new job. Some concerns express the relation between diameters in other ways than as "per cent reduction." Thus the 40 per cent reduction as from 10 in. to 6 in. in diameter may also be written as 10 in. × 0.60 (60 per cent) or 6 in. × 1.67 (167 per cent). The small cross-scale under the formula in the chart is arranged for the relative conversion of such values.

Methods of Redrawing.—Returning to Fig. 148, sketches *A*, *B* and *C* illustrate three arrangements of double-action redrawing dies for use in

double-action toggle or cam presses. Such dies may also be inverted and used in single-action presses equipped with air, rubber or spring drawing attachments. In the case of double-action presses, shells without flanges may be pushed through the die and discharged that way, with some attendant advantage in production.

In Fig. 148 *A*, the face of the punch and the blank-holding surface are flat, and the bottom of the previous shell was flat. This is the easiest way to make the tools, but it is not the easiest on the material. It is evident that the metal in the side-walls must make two right-angle bends in its progress through the die.

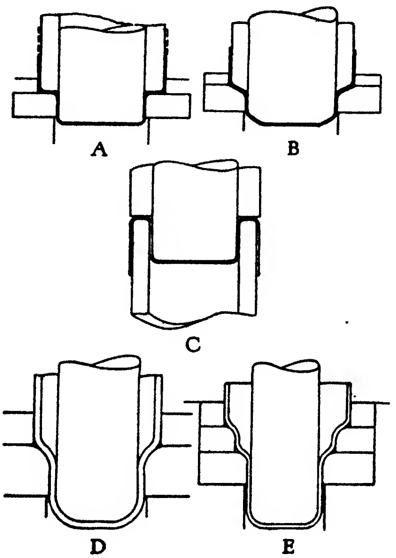


Fig. 148.—Double-action redrawing (*a*, *b*, *c*), reverse redrawing (*c*), and single action redrawing (*d* and *e*).

The tool arrangement shown in Fig. 148 *B* eases this situation somewhat as the blank-holding surfaces are finished at, say, 30°, reducing the two bends to 60° each. The path of the metal through the tools being easier and more direct also assists in easing the draw by reducing the strain in the shell wall due to friction. Punch faces must, of course, be finished at an angle to prepare the bottom of the shell to receive the angular blank-holder. This bevel on the punch faces tends to give the metal an opportunity to wrinkle just as the draw begins. For that reason, angles greater than 30° are rare. Even a small angle will sometimes make it possible to "get away with" a troublesome reduction especially where the metal is thin relative to the diameter and the bottom is tearing out.

Fig. 148 *C* shows a reverse redraw in which the shell is being turned inside out. Although the metal must still make two 90° bends, the flexure is all in one direction instead of reversing itself. Some shops consider that this method of redrawing gives better control and less likelihood of wrinkles at the start, especially in redrawing rectangular shapes.

Fig. 148 *D* and *E* illustrate single-action reducing in which there is no blank-holding action. The first (*D*) is typical of common practice. The essential qualification, as has been discussed, is that the metal be

thick enough relative to the diameter to resist the tendency to wrinkle in the area normally supported by the blank-holder. Compared with sketch *A*, we no longer have the frictional resistance due to bending over the outer edge of the blank-holding ring. Compared with sketch *B*, we obtain an easier and more direct flow by the use of large-radius bends, which in turn is made possible by the relative thickness of the material.

It would seem logical then that larger reductions should be obtainable in single-action redrawing than in double-action work. The limiting factor is preventing wrinkles from forming. Extremely thick material should do it. Fig. 148 *E* illustrates another method, the stepped die. The double flexure seems unnecessarily severe, but its effect is to set up corrugations or reenforcing ribs in the area where strong circumferential compressive stresses are likely to cause wrinkles. By this method single-action reductions in excess of 35 per cent have been recorded in metal having a thickness of 3 per cent or more of the diameter, Fig. 126.

A drawing operation begins with a flat sheet of metal of (practically) uniform thickness. It ends with a drawn shell the bottom of which is of the original thickness because it has been subject to little or no stress. The side-walls, however, consist of more and less severely worked material, and their thickness will be found to vary measurably *both above* and *below* the initial thickness.

It is possible to predict such variations in wall thickness approximately and, by an understanding of their causes, to partially control them to the benefit of the product. Upon occasion the wall thickness may be arbitrarily increased or decreased by upsetting or ironing, respectively.

Natural Increase in Wall Thickness.—In any round drawing or redrawing operation, metal in the flange of the shell, between the blank-holding surfaces, is increased in thickness as it is reduced in circumference. The mechanical aspect of this was discussed in connection with Fig. 140. The (constant) volume of any unit portion of the metal is the basis for computing the dimensional changes.

In Fig. 149 are shown two drawn shells, it being assumed that one is reduced from the other in a series of dies having sufficient clearance to permit the metal to thicken up naturally. If two lines are scribed around the first shell, separated by a distance t equal to the wall thickness at that point, they will serve to mark off a band of metal (indicated by shading) having a volume $v = t \times t \times \pi d$, in which d is the mean diameter of the shell.

After the reductions the diameter has become d_1, and if the metal structure is uniform the cross-section of the marked band will still be

square, having a new thickness and height of t_1 and volume of $t_1 \times t_1 \times \pi d_1$. As volume is not changed by the reductions, the two expressions may be equated.

That is:

$$t^2 \times \pi d = v = t_1^2 \times \pi d_1$$

or in order to find the new thickness:

$$t_1 = t\sqrt{d/d_1} \tag{28}$$

If we deal instead with an increment of height, h, the formula becomes:

$$h_1 = h\sqrt{d/d_1} \tag{29}$$

The nomogram, Chart VII in the Appendix, may be used in approximating changes of wall thickness and height in proportion to diameter. It must be remembered, however, that the results are modified somewhat by certain tendencies to decrease instead of increase the wall thickness.

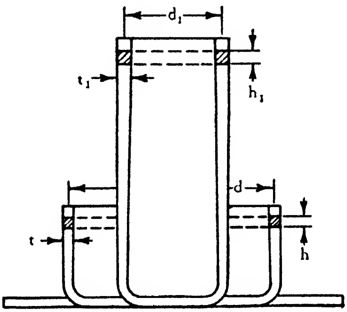


FIG. 149.—The manner in which the thickness and height of a given volume of metal increase as the diameter of the shell is reduced.

Natural Decrease in Wall Thickness.—In the discussion of bending metal, in connection with Fig. 77, it was pointed out that the metal moves more easily on the tension side of a bend, owing to decreasing resistance, and less easily on the compression side, owing to increasing resistance. For this reason, when a piece of metal is bent sharply its mean length is increased (slightly) and its thickness is decreased at the bend. It was cited, by way of example, that metal 0.250 in. thick was reduced to 0.243 in. in thickness when bent over a ½-in. radius and to 0.237 in. in thickness when bent over a ¼-in. radius. This also brings out the point that a sharper radius reduces the metal thickness to a greater extent.

In drawing operations, the metal which becomes the side-walls of the shell is really bent or flexed twice. That is, it is made to conform to the radiused edge of the draw die, and then pulled out straight again. In reducing operations the metal is flexed four times as it bends into the blank-holding area and then out again. This was illustrated in Fig. 148 *A* and *B*.

Ordinarily the amount the walls are thinned by flexing is relatively little because the *radius of the draw die* is comparatively large, say

four to six times the metal thickness. This may be reduced to $2\frac{1}{2}t$ for stainless steel or less for organic plastics, or increased over $6t$ for Alclad. It must not be too large, as that would permit the metal to get out of control and form wrinkles.

A sharp radius on the drawing punch causes considerable thinning around the bottom due again to bending. This is illustrated in Figs. 150 and 152. For this reason a small radius is undesirable on punches for the early operations in a series of reductions. It is apparent that such a thin line will reappear higher and higher up the shell wall as the diameter is reduced, leaving a relative local weakness.

One other cause of shell walls becoming thinner in work is the severe tensile stress set up in the walls due to large reductions per operation. Fig. 137 illustrates the manner in which the tensile stress in the wall rises from a point below the elastic limit, in the case of a small reduction, to a limit draw with a wall stress near the true ultimate strength where the metal is likely to neck and break or tear at the weakest point, which is usually the bottom radius.

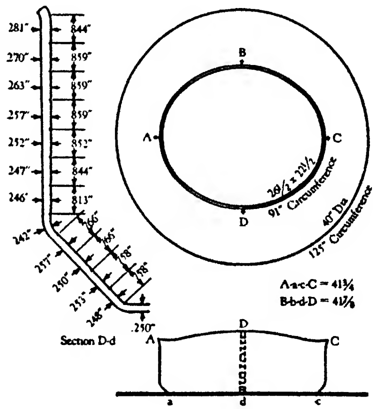


Fig. 150.—A blank marked and drawn experimentally into an oval shell in exploring the changes in width, height and thickness of unit volumes in the walls.

Fig. 150 shows the results of an experiment conducted to show the natural metal movement. A 40-in. diameter blank of ¼-in. boilerplate was marked off into ¾-in. squares on a planer with a result similar to that shown in Fig. 117. It was then drawn into an oval shell having a long axis of 26½ in. and a short axis of 22½ in. Fig. 151 shows the equipment in which this was done, set up on the test floor. The die in use, however, is one for an operation near the end of the series, as the shells show. It is of interest to note that the press is equipped with an air-operated die slide permitting it to handle shells higher than its stroke would normally accommodate. There was an additional advantage in that the shells weigh about 90 lb., and the forward position of the die slide permitted the use of an air hoist to handle them in production.

The experimental blank was placed in the drawing die (first operation) so that the coordinates of its markings coincided with the long and short diameters (A–C and B–D) of the die. This permitted easy measurement of the vertical (v) and horizontal (h) dimensions of those

ex-squares which came in the side-walls under the points A, B, C and D. The results are given in tabular form below. From these a sectional

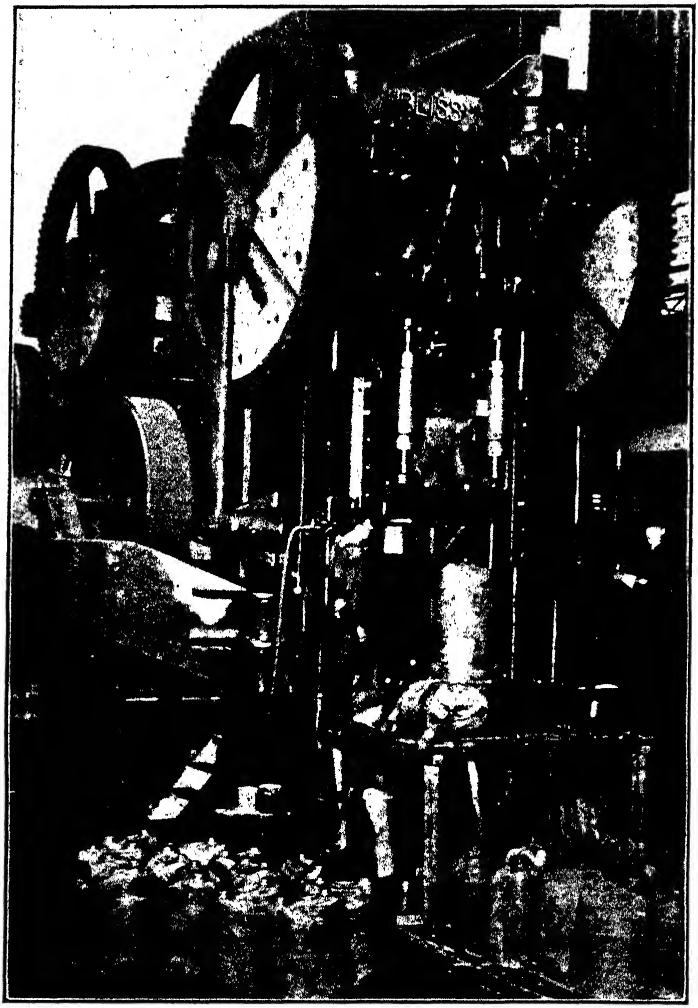


FIG. 151.—The equipment used for the experiment illustrated in Fig. 150, except that the tools have been changed for a later operation. The tools actually used are shown in Fig. 171.

strip, below the point D, is reconstructed in Fig. 150. The section illustrates the thinning at the corner and thickening toward the top.

Slight inaccuracies are apparent in the above and are chargeable both to the method and to normal non-uniformity of structure of the

material. The circumference of the original blank was 125 in., whereas that of the shell was 91 in., an average reduction of about 27 per cent. The greatest reduction in width of single square was on the shorter radius under *A* and amounted to about 31 per cent. That on the longer radius under *D* was about 21 per cent.

Table XV

DEFORMATION OF ¾ BY ¾ IN. RULINGS, FIG. 150

$A - a$	$B - b$	$C - c$	$D - d$
v *h*	*v* *h*	*v* *h*	*v* *h*
	0.843 by 0.656		0.844 by 0.594
	0.868 by 0.601		0.859 by 0.609
	0.859 by 0 609		0.859 by 0.625
0.910 by 0.520	0.859 by 0.630	0.890 by 0.531	0.859 by 0.633
0.872 by 0.570	0.844 by 0.656	0.859 by 0.572	0.852 by 0.656
0.855 by 0.610	0.821 by 0.687	0.851 by 0.609	0.844 by 0.676
0.835 by 0.640	0.773 by 0 700	0.822 by 0.640	0.813 by 0.703
bend 0.670	bend 0 719	bend 0.679	bend 0.719
0.773 by 0.695	0.773 by 0.726	0.765 by 0.707	0.766 by 0.719
0.765 by 0.710	0 775 by 0.734	0.770 by 0.718	0.766 by 0.734
0.757 by 0.734	0.750 by 0.745	0.745 by 0.750	0.758 by 0.734
0.750 by 0.742	0.750 by 0.750	0.750 by 0.750	0.758 by 0.750

Fig. 152, showing, in cross-section, three stages in the reduction of a ferrule, illustrates thinning around the bottom corner due to small punch radii. The walls do not show the thickening toward the top

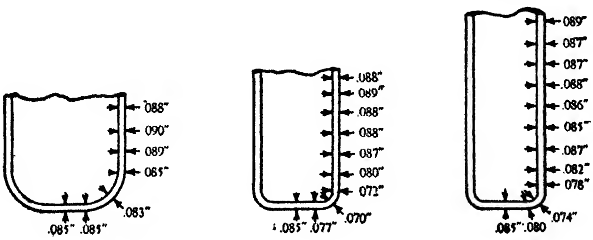


Fig. 152.—The dies were arranged for restricted ironing to prevent thickening. Thinning at the bottom was increased by the small corner radius.

which might be anticipated, however. Such thickening undoubtedly did occur during the reduction but was immediately ironed or squeezed

back. This was accomplished by finishing the punch and die to diameters which left only space or clearance for the desired thickness between them.

Ironing.—Fig. 153 illustrates diagrammatically a typical ironing operation. The heavy line represents the wall of a shell partially drawn through the die, in which process its wall thickness is being reduced to nearly a half of what it had been, and its inside diameter is being reduced by a small amount. Since the principal need in this case is to reduce the wall thickness, the reduction in diameter is merely enough to permit the punch to enter freely. This is the opposite extreme from Fig. 152, in which reduction in diameter was the primary function and ironing was merely enough to counteract or correct the natural increase in wall thickness due to drawing.

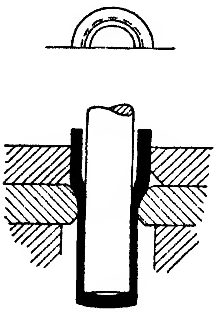


FIG. 153.—An ironing operation partially completed, showing changes in diameter and wall thickness.

The ironing process is readily adapted to the production of shells having walls which are tapered or stepped to a non-uniform thickness. Thus Fig. 154 shows the series of operations involved in reducing and ironing both the steel bullet cap and the brass case for a rifle bullet. The original metal thickness is retained in the bottom of each shell up to the stage of forming the point of the bullet and of indenting the base of the case. The side-walls of both are ironed thinner with each reduction. The punches, which are tapered, determine the inside shape of the shells, and as the dies leave the outside straight and parallel, the walls are tapered from considerable thickness at the bottom to a very thin section at the top.

To illustrate the effect of the plastic cycle upon the metal structure in drawing and ironing, a group of photomicrographs was prepared of one of the operations in the production of caliber 0.30 cartridge cases from 70 : 30 soft-temper drawing brass. As shown by Fig. 154, the part is first blanked from the strip and drawn into a cup with a slight wall reduction, after which it is annealed and pickled. Then it undergoes four severe reductions which are largely ironing, and is annealed (restored) after each, which brings it to the stage at which the photomicrographs, Fig. 155, were taken. In the course of these five operations (five plastic cycles), it may be shown that a unit block or particle of metal near the edge of the original blank has been subject to total elongation of about 1300 per cent, or a transverse reduction of about 93 per cent.

The physical specifications of the brass called for an elongation (general) of 52 per cent in 2 in. The actual reduction per step amounted to nearly 50 per cent, which is the equivalent of nearly 100 per cent elongation. This brings the stresses at each reduction clearly in the range of the necked portion of a tensile specimen and to the stage described as extra hard temper in Fig. 127.

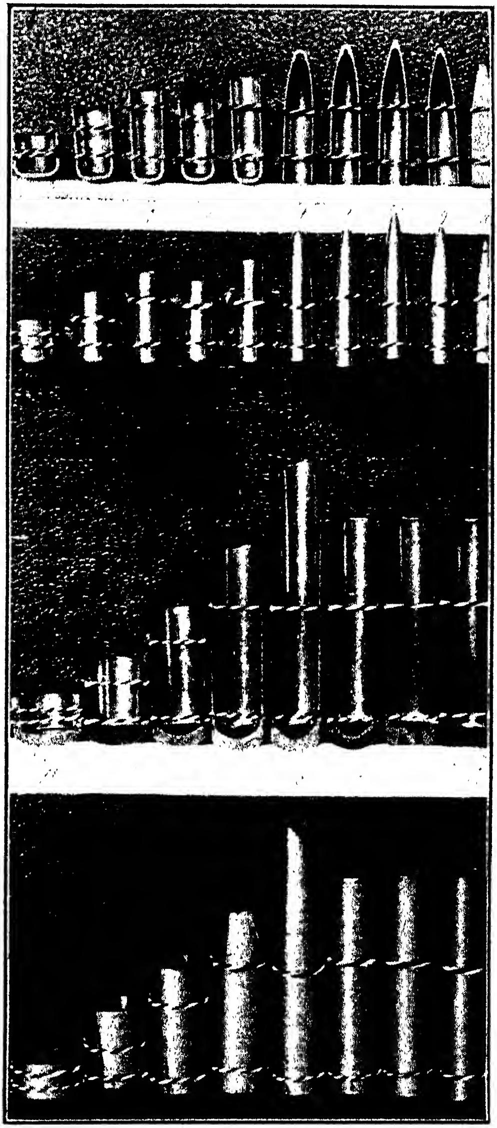


FIG. 154.—Ironing operations in the production of steel bullet jackets and brass shell cases.

In Fig. 155, the photos *A* and *B* were taken [3] after the fourth ironing operation with the metal still in the strain-hardened state. Photos *C* and *D* were taken after annealing in preparation for the next operation.

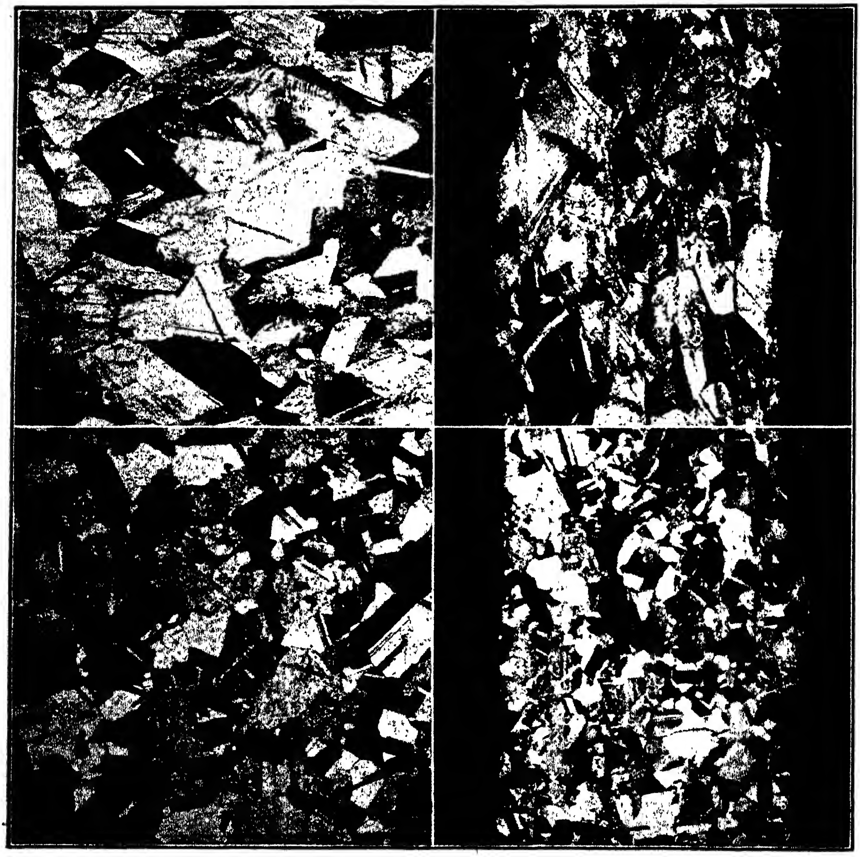
Photo *A* shows the condition of the crystals in the bottom of the shell and toward one side. There was a slight but noticeable distortion of the metal in this area, and the crystals show some evidences of slip-plane movement. Slip lines were not at all apparent further in toward the center of the bottom where no movement took place.

Photo *B* shows a section of the severely worked side-wall of the shell. The outlines of the old crystals are still present, but many

[3] Samples sawed in half lengthwise, polished and etched for ½ to ¾ minute in a solution of about 1 part hydrogen peroxide in 20 parts ammonium hydroxide. Photographed at 100 magnifications.

groups of lines traversing them mark the passage of slip-plane movements. A higher magnification of a similar area was shown in Fig. 128. The reduction involved has strain-hardened the metal to approximately

A B



C D

FIG. 155.—A cartridge case after the fourth draw, ×100, showing the bottom (*A*) and wall (*B*) after ironing (nearly 50 per cent reduction); and the bottom (*C*) and wall (*D*) after limited annealing.

extra-hard temper which is approaching the upper plastic limit for this metal.

Photo *C* shows the bottom of the shell again, but after annealing. In a number of the contrasting twin crystals are apparent the straight boundary lines which characterize an unstrained structure in brass. Corresponding lines in photo *A* show some distortion, and in photo *B* there appear to be no really straight lines.

Photo *D* shows the side-wall after annealing. The structure is unstrained, but the average crystal size is much less than it was before the last draw, as indicated by the old grain boundaries in *A* and *B*. This smaller size was obtained intentionally in the annealing in order to retain some stiffness at the mouth of the shell. Thus, referring to Fig. 127, the anneal was carried through recrystallization to a point corresponding to a 30-minute anneal at 600 or 700° F. where relatively little grain growth has taken place. Here the physical properties of the side-wall correspond in a general way to the quarter-hard temper obtained by cold-working except that the crystals remain whole and unstrained.

The actual anneal in this case was the regular production operation in which the shells take 7 to 8 minutes passing through an electric furnace heated to 1300° F. It may be noted that crystal size is larger in the bottom, *C*, than in the side-wall, *D*, on account of differences in cold-working. An excellent and detailed study of variations in grain structure and physical properties of cartridge cases with differences in mechanical working and heat treatment has been prepared from the government's war-time experiences and is available in the records of the A.I.M.M.E.[4]

In drawing cartridge cases, the amount of ironing usually varies around 35 to 68 per cent reduction in thickness per operation. This is preceded in the same operation by a small reduction in diameter of from 0.020 in. to perhaps 6 or 8 per cent. In the first operation cup, the ironing load, formula 30, really occurs after the drawing load, which is less than indicated by formula 22, being performed single action. In checking cold work, however, the drawing reduction, r_1, and the ironing reduction, r_2, should be added: $r_n = r_1 + r_2\ (1.00 - r_1)$.

Ironing or crowding back a portion of the shell wall is in the nature of coining, as indicated by the burnished surface of the metal. It obviously adds to the normal drawing load an amount proportionate to the projected section area worked away. The working pressure, P (pounds), due to ironing may be approximated by the formula:

$$P = \pi d i S \tag{30}$$

in which d = mean working diameter, in inches, or outside diameter after ironing, plus i;
i = reduction in wall thickness, in inches;
S = compressive unit stress, or yield point of the strain-hardened metal, pounds per square inch.

[4] J. B. Read and S. Tour, "Testing Artillery Cartridge Cases," A.I.M.M.E. No 1151 N. March. 1922.

Comparing formula 30 and Chart VIII in Appendix I, note that the chart has been simplified by the use of the outside diameter of the finished shell instead of the mean working diameter, which would be slightly greater. This is taken care of in the arbitrary addition of a 20 per cent constant designed principally to cover friction.

The theoretical *maximum reduction* in wall thickness per operation due to ironing is approximately *50 per cent,* though reductions up to 64 per cent * have been recorded. The latter figure indicates that the cross-section area of the initially annealed metal which is being displaced is greater than the area of the strain-hardened metal which must transmit the pulling strain. This apparent unbalance is probably compensated by the increase in strength due to working.

If the shell wall is ironed thinner by a uniform amount for the entire length of the shell, then the work done in ironing is approximately the product of the length of the shell or the ironed surface (l, inches) and the pressure required for ironing from formula 30:

$$W = P\,l \tag{31}$$

The work, W, will be in inch-pounds or inch-tons depending upon whether the pressure, P, is given in pounds or in tons. This formula applies to most cartridge-case operations. *If a reducing operation accompanies ironing, then the drawing pressure must be added to the ironing pressure,* except that in cartridge cupping, one largely precedes the other.

If the ironing operation is merely to correct the natural changes in wall thickness due to drawing, and reduces the thickest portion of the wall near the top of the shell to equal the thinnest portion near the bottom, the average ironing pressure will equal about half the maximum:

$$W = 0.5\,P\,l \tag{31a}$$

Drawing Rectangular and Irregular Shapes.—Fig. 150 and the accompanying table showed, by the amount the marked squares had been deformed, that the stresses in the metal due to drawing were not the same in the ends and in the sides of the oval. At the ends the shorter radius caused a greater compressive movement amounting to as much as 29 to 31 per cent, compared with a maximum of only 18 to 20 per cent in the sides of the oval.

The same is true to an even greater extent in rectangular shells. Fig. 156 gives outlines of the blank, first draw and final draw for a two-draw rectangular shell. At one corner is indicated (in full lines)

* "Cold Working of Cartridge Brass," Frank J. Lerro, Artillery Case Shop, Frankford Arsenal, The Modern Industrial Press, February, 1940.

the manner in which the stock would have to be cut to fold up into the first shell without drawing. See also Fig. 136 at the right. The space between the fingers indicates the amount of metal that must be crowded out in the process of drawing. This involves severe internal stress in the metal in the corner area as compared with freedom from internal stress in the side-wall area where only bending occurs. Therefore a portion of the surplus metal tends to be thrust out from the corner area into the side-wall area. Hence the development of a blank which would just fill the corner of the drawn box level with the sides would approximately follow the dotted line. This is also illustrated in Fig. 157.

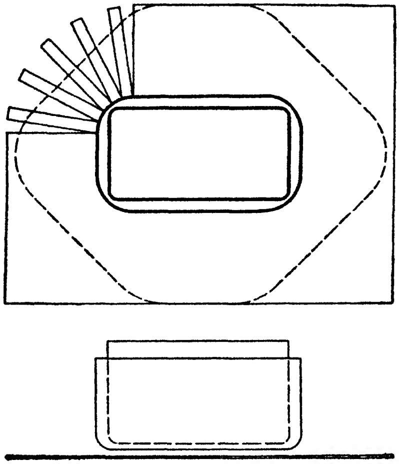


Fig. 156.—A blank and two steps in drawing for a rectangular shell, illustrating the corner displacement.

In some cases the combination of the depth of draw, metal thickness and draw radius makes it difficult to hold such metal back in sufficient control to prevent wrinkling in the corners. A cure employed for this is to use a plain rectangular blank instead of a developed blank. As shown in Fig. 158, this results in tabs at the corners which the blank-holding surfaces can grip to help hold back the surplus corner material. Draw beads or corrugations may even be added in the blank-holding surfaces to help in gripping these tabs.

Fig. 157.—A drawn sardine box, which is not trimmed, and the developed blank for it.

The metal in the corners thickens up, and that in the side-walls does not. Therefore it is sometimes necessary to relieve the blank-holding surfaces at the corners, so that improperly held metal in the sides does not wrinkle.

The fact that metal in the corners of a drawn shell has been worked more severely than that in the sides, naturally tends to cause warping in annealing or enamel baking. It has been said that by using a very sharp drawing edge along the sides of the die, and a normal radius edge at the corners, metal in the sides can be over-stressed sufficiently to obtain a fair balance of internal stresses.

In drawing a plain round shell, the limit draw in one operation is usually such as to give a shell depth about equal to its diameter or to twice its radius. In drawing rectangular shells, however, the limit *depth per operation is about four to six times the corner radius,* owing to distribution of surplus metal from the corner area into the adjacent

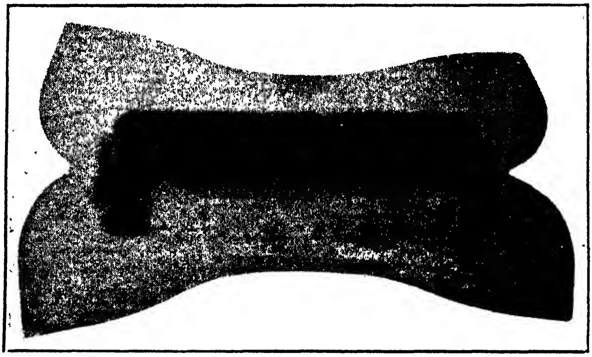


FIG. 158.—A rectangular, sheared blank was used for this crankcase shell, to give increased holding surface at the corners.

side-wall area. The modifying effects of metal thickness, bottom corner radius and ironing are about as has been discussed for plain round shells.

In redrawing rectangular shells, as illustrated in Fig. 156, it is necessary to work from a larger radius to a smaller radius, and also to keep the two radii as close together as is consistent with blank-holder corner strength, to avoid wrinkling. Reverse redrawing about in accordance with Fig. 148 *C* but without the blank-holding ring is about the only method of single-action redrawing for rectangular work of any depth.

To compute the drawing load for a rectangular or irregular shape it has been common practice to multiply the periphery of the shell by the thickness and the nominal ultimate tensile strength of the metal. As in formula 21, this gives the *load to pull the bottom out of the shell,* which is a safe maximum where no ironing is involved, but is usually quite a bit more than necessary. A formula for the drawing load for rectangular shells should distinguish, on the one hand, between the straight side-wall areas where bending and friction only are involved and stresses are

low, and on the other hand, the corner areas where, in addition, the high compressive stresses necessary to rearrange the metal are occurring in the flange area. Accordingly, following formula 21, let us write:

$$P = \pi d t S = 2 \pi r t S C_1$$

for the four corner areas, plus $LtSC_2$ for the straight side sections, or

$$P = t S (2\pi r C_1 + L C_2) \tag{32}$$

in which P = drawing punch pressure in pounds;
t = metal thickness in inches;
S = nominal ultimate tensile strength, pounds per square inch;
r = corner radius of the rectangular shell, inches;
L = total length of straight sides of rectangular shell, inches;
Constant — C_1 = 0.5 for a very low shell up to say 2 for a shell having a depth of five or six times the corner radius, r;
Constant — C_2 = say 0.2 for easy draw radius, ample clearance and no holding pressure, or say 0.3 for similar free flow and a normal blank-holding pressure of about $P/3$, or a maximum of 1 with the metal clamped too tightly to flow. These arbitrary values for C_1 and C_2, concerning which judgment must be used, might well be the subject of an extended investigation.

The low values for C_2 are based upon the experimental results shown in Figs. 136 and 137. Blanks were cut out so that they would fold up into the shape of a shell to test the loads due to bending only, with and without blank-holding pressure. These experiments should be continued with different radii and clearances.

The values given for C_1 are entirely arbitrary though they might readily be determined (by difference) in a suitable experimental equipment. The maximum value for this constant would be 1 for round work of maximum depth, as that would represent the load to pull the bottom out of the shell. In rectangular jobs the flow of surplus material into adjacent side-wall areas makes possible greater relative depths per draw in the ratio of 2 or 3 to 1 on the radius. This flow into the side areas raises the drawing load there above that covered by C_2, and the logical place to allow for it is in the computation of the corner load. For that reason the value 2 is suggested as a maximum for C_1 with suitable allowance for lower shells.

The work done in the free drawing of a rectangular shell may be determined as in formula 24 by multiplying the maximum drawing pressure by the depth of draw by a factor rising from 0.60 to 0.80 as the depth of draw increases to a maximum.

It is advisable at this point to mention a method of computing the punch *pressure required for* those *shallow shapes* which are stretched over the nose of the punch without actual drawing. A case of this sort was illustrated in Fig. 142. To give the metal permanent set, the stress in it, parallel to the shape surface, must exceed the elastic limit of the metal, considering the temper used. The punch pressure, P, is then the vertical component of the elastic limit at the angle at which the shape meets the blank-holding surface (Fig. 142):

$$P = LtS_e \sin a \tag{33}$$

in which L = punch periphery in inches;
t = metal thickness in inches;
S_e = elastic limit of metal as furnished, pounds per square inch;
a = angle of incidence of shape and blank-holding surface; see Fig. 142.

Classification of Dies.—In classifying dies and methods belonging to the drawing group of press operations, perhaps the most general distinction is whether the shell is pushed through the die or returned to the surface of the die to be pushed off. Shells drawn without leaving a flange, and without any forming or stamping operation at the bottom of the stroke, can be pushed through the die and discharged under the press without further handling. This is limited, however, to single-action operations in single-action presses and double-action operations in double-action presses. If automatic feeds are used on a push-through job, as in Fig. 159, it is advisable that three spring-actuated stripper fingers be built into the die holder under the draw ring as shown in Fig. 160. This necessitates a longer press stroke but makes stripping positive. The elasticity of the metal and internal strains from drawing make shells tend to stay in the die, but that is not sufficiently positive for automatic operation.

When shells require a flange or a stamped impression in the bottom, or when double-action dies are used in single-action presses, or triple-action dies are used in double-action presses, the work cannot be pushed through the die. Accordingly, spring pad knockouts may be used to get shells out of the die, but it is more positive and therefore preferable to use lift-out pads (Fig. 161) operated from under the press-bed, or

knockout pads (Fig. 162) operated from a bar or lever in the press slide. Either type of knockout may take its movement directly from the press slide or may be separately cam-actuated to do the ejecting at a point earlier than top stroke.

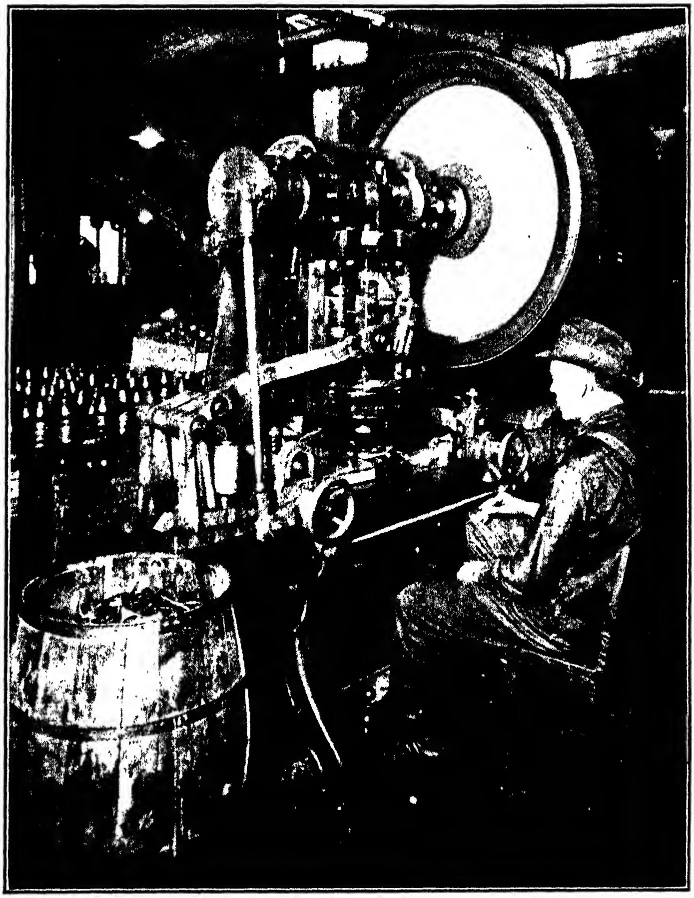


Fig. 159.—A double-action cam press equipped with a combination die, blanking and drawing a shell and pushing it out through the die.

Shells may sometimes stick to the punch, because of oil or a suction resulting from lack of a proper air vent. In double- and triple-action dies the blank-holding ring serves as a stripper to prevent this, although vents should always be furnished. In single-action work a simple stripper may be used consisting of a stripper plate to fit the punch, two long rods through the bolster to limit its upward travel to about mid-

stroke and two tension springs to cause it to follow the punch up. Parts for such a stripper are shown in Fig. 163.

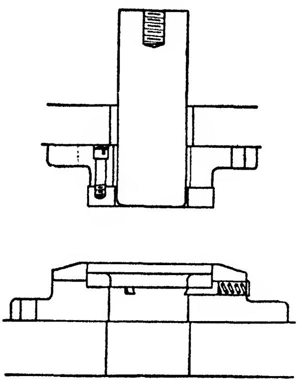


FIG. 160.—A double-action combination die with spring stripper fingers for automatic operation.

Single, Double and Triple Action.—These designations are applied to both dies and presses according to the number of vital moving members.

Thus Fig. 164 shows a typical single-action press, having only the one slide, and single-action tools, in which only the punch moves. Fig. 163 illustrates a typical set of single-action redrawing or reducing punches and dies. The production is not large in this case, so that all the die rings are made to fit a common holder. Further illustrations of the single-action type of tools include cross-sections of a draw die in Fig. 143 and of one- and two-step redraw dies in Fig. 148.

Typical double-action drawing and re-drawing dies are found in Figs. 161, 165 and 170. The punch and blank-holding ring, which are the moving members, are carried on the

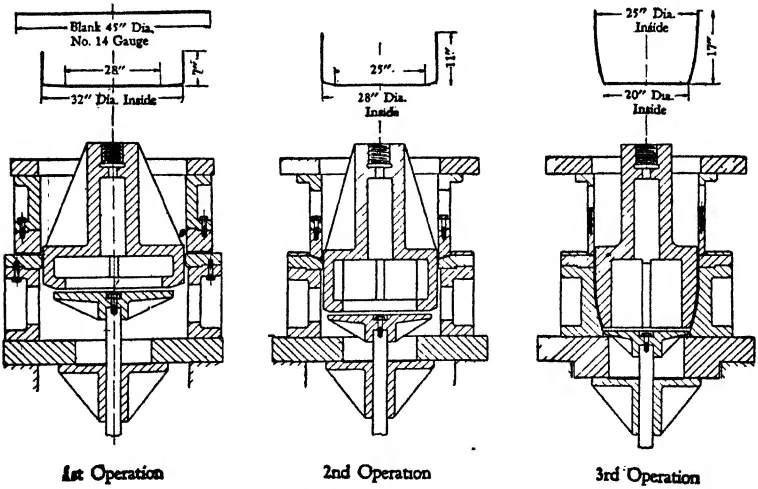


FIG. 161.—First, second and third operation double-action drawing dies for half barrels.

inside and outside slides respectively of cam or toggle presses. Figs. 162, 166 and 168 also represent double-action dies but of the inverted

type used in single-action presses. Here the moving members are the die, which is mounted on the single press slide, and the blank-holding ring which is carried on pins through the bolster to a pneumatic, spring or rubber drawing attachment suspended under the bed of the press.

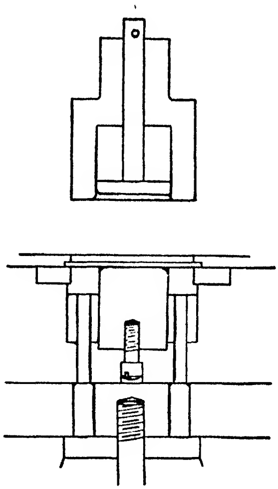


Fig. 162.—A double-action combination die of inverted type for use in a single-action press.

Fig. 167 illustrates a typical triple-action die for two drawing operations. At the right is the die with a spring blank-holding ring around it. At the left is the mechanically actuated upper blank-holding ring which performs the first draw. It then dwells for the punch, in the background, to make the second draw. Such a method may be used for many shapes so long as the metal will stand the continued working without annealing. In this case the die is arranged for a double-action press with a drawing attachment in the bed. Triple-action presses,[5] especially built for such work, have, for example, an underneath die slide which holds the blank up against a fixed bed while an upper slide draws and then holds the resultant shell for a second upper slide (punch slide) to redraw the metal.

Combination Dies.—The dies in Fig. 160 and in the upper left corner of Fig. 172 are typical *combination blanking and drawing dies* of the push-through type for use in double-action presses. Fig. 162 shows a combination die for use in a single-action press. Note that it is usually necessary to make the upper member or punch in one piece as shown, with the result that the drawing radius must be redressed every time the cutting edge is ground. This disadvantage does not apply to the type first mentioned.

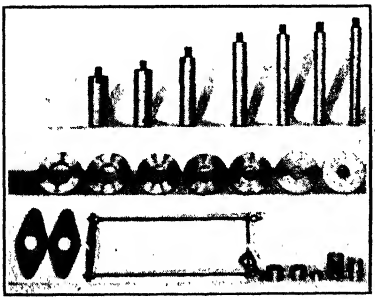


Fig. 163.—A series of punches, die rings and punch stripper plates for single-action redrawing.

Fig. 168 *a* is a can bottom combination die which includes stamping with blanking and drawing. Fig. 168 *b* goes a step farther and pierces the center hole, a thing which is possible only in this inverted type of

[5] See discussion of triple-action presses in Chapter XIII.

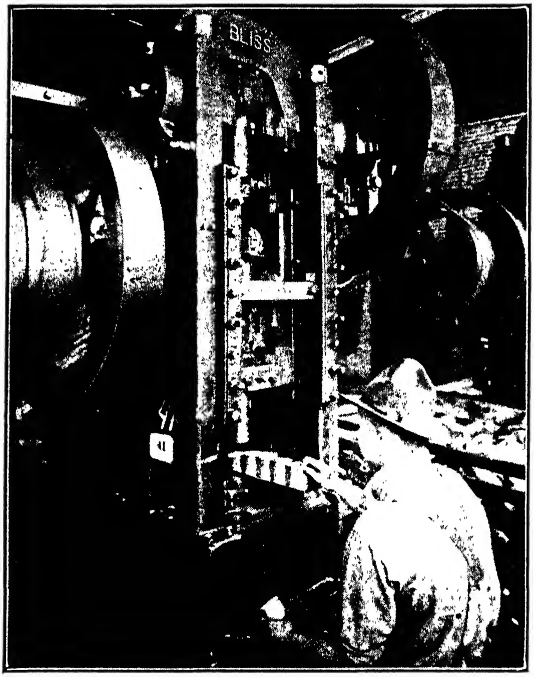


FIG. 164.—A single-action press and single-action die on a reducing operation.

die used in single-action presses. As can-end production is ordinarily large, such dies are usually run in automatic strip feed presses with cam knockouts and air ejection. It is anticipated, however, with the advent of coil tin plate and high-production (roll feed) presses that this practice will soon be changed, considerably increasing speed and economy.

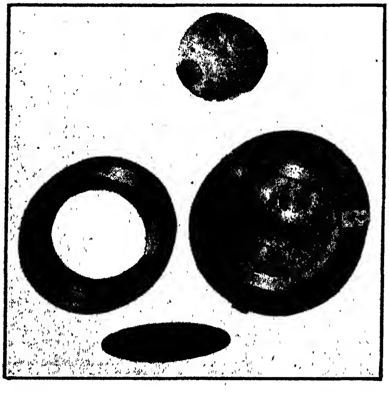


FIG. 165.—A double-action "tank end" die combining drawing and stamping.

Cutting and cupping dies,[6] as their name implies, are combination dies which cut out a blank and draw it into a cup, pushing it through the die. They differ from other combination dies, however, in that they are practically single-action drawing dies. The relation of shell diameter to depth and

[6] Similar in principle to Fig. 160.

metal thickness is such that little or no blank-holding effect is required. The presses used are the double-action crank type [7] in which both the outside and inside slides are crank-actuated with the timing so arranged that a very brief dwell is obtained. These presses are materially faster than the cam and toggle types.

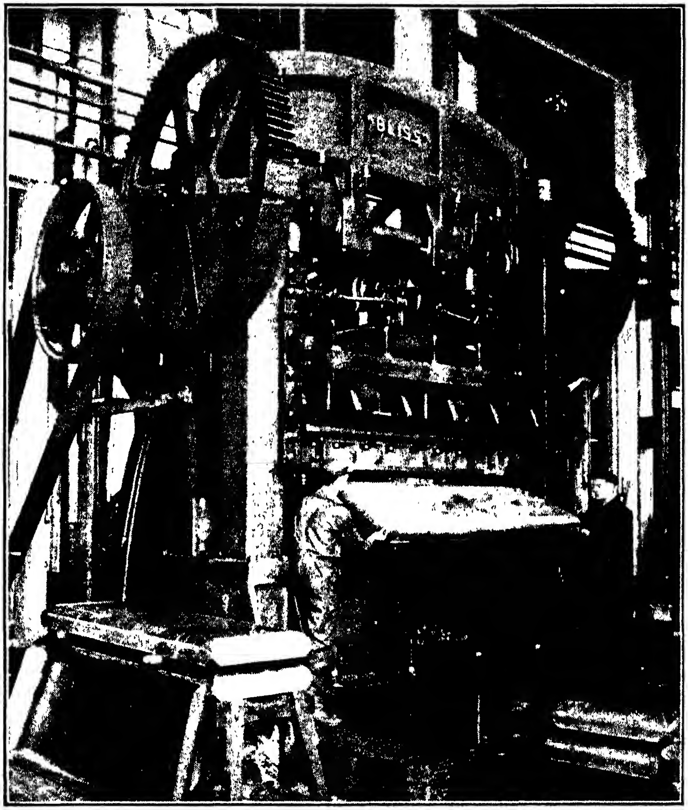


FIG. 166.—A single-action press with spring drawing attachment and double-action die, producing a large casket part.

Single-action combination work might be the heading for a group of forming and blanking operations in which the face of the blanking punch is shaped to do shallow forming during or immediately before or after cutting. The shape or the metal thickness must be such that a blank-holder is unnecessary.

Miscellaneous Draw Die Types.—Double dies are advantageous in that some drawn shapes may be held easily on three sides but not on the

[7] See Fig. 282.

fourth. Then, as in Fig. 169, two of them may be drawn back to back giving a good holding flange all around. Later they are separated in a parting or double trimming die. In single-action presses with drawing

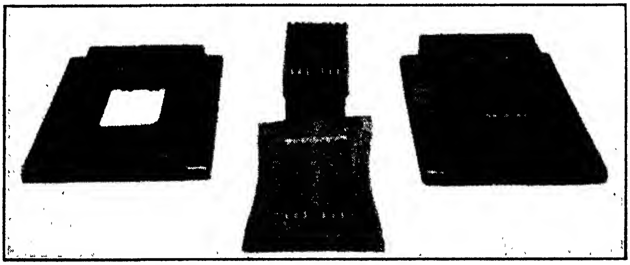


Fig. 167.—A triple-action die for producing a two-draw stamping in a double-action press with an auxiliary drawing attachment under the bed.

attachments the two pieces may be parted at the end of the drawing stroke.

Fig. 169 also illustrates very well the use of draw beads or mouldings to assist in holding the flange. Such a practice is often necessary,

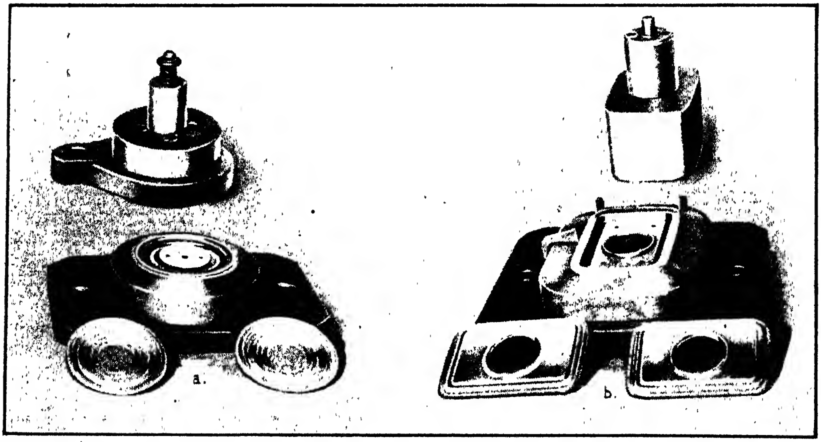


Fig. 168.—(*a*) A combination blanking, drawing and stamping die. (*b*) A combination blanking, drawing, stamping and piercing die.

in the case of irregular contours and reverse curves, to get sufficient grip on the metal to make it follow the punch at the difficult points. Shallow shapes with a slight surface curvature are also likely to require beads in order to stretch the metal beyond its elastic limit and make it

hold its shape. Fig. 170, showing (above) the die and punch, and (below) the blank-holder ring and a sample panel, illustrates a method of inserting draw beads.

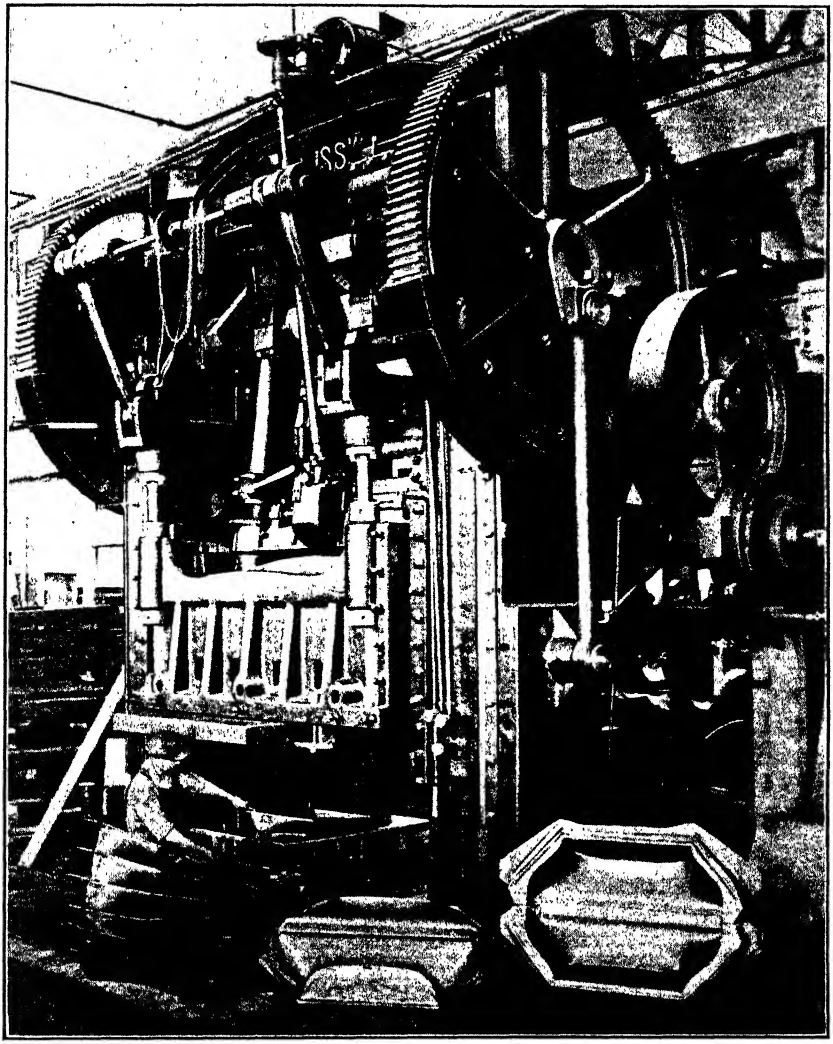


FIG. 169.—A double die for an unbalanced part, with reverse curves which necessitate the use of draw beads. Double-action press and die.

Stamping operations are frequently combined with drawing, as in Figs. 165 and 168. In such cases the load at the end of the press stroke, to flatten the bottom or to stamp a design, lettering or a depression, is

often if not usually greater than the drawing load. In fact, poor die design or careless setting up of jobs in this group is responsible for the majority of all press breakages.

"Hit-home" stamping operations[8] may take anything between *5 and 100 or more tons per square inch* of striking or squeezing area,

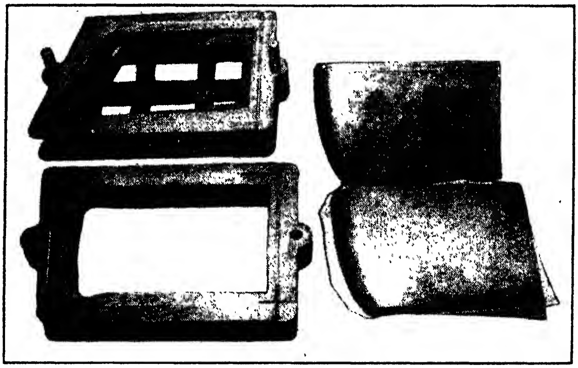


FIG. 170.—A double-action die for a shallow draw, illustrating the use of draw beads.

depending entirely upon the set-up of the press. Clearly such jobs place an excessive risk upon the ability of die-setters. It is better therefore to cut letters, beads, etc., extra deep so that the tools bend or draw the metal rather than stamp it. When it is necessary to strike a corner

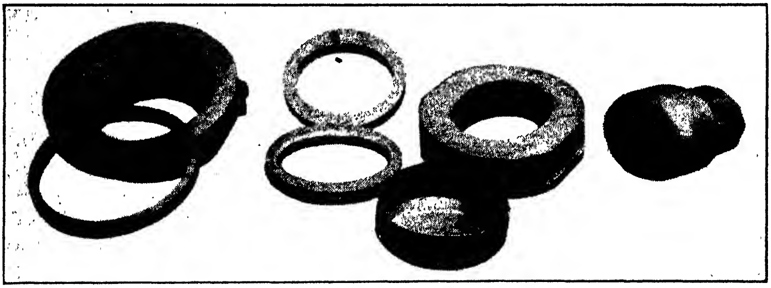


FIG. 171.—A double-action die for a ¼-in. steel shell. The holder with shrunk steel ring is used for several operations.

or outline to get a sharp impression, the striking surfaces should be so relieved that contact is made only along a narrow line right at the point where the impression is required.

In Fig. 165 the stamping pad serves also as a knockout, bottoming solidly on the bolster plate at bottom stroke for the stamping operation.

[8] Fast acting hydraulic presses are often especially suitable. See Fig. 183a.

It is shown in the die. The punch, which serves both for drawing and stamping, is above. The die is fitted with three simple gauge pieces for the location of the blank.

Fig. 163 showed a series of redraw die rings to be used in a common holder. Fig. 171 shows, at the left, a holder used for series of four draws. At the right are the punch and blank and blank-holder, and in the center are the draw ring and filler ring for the shell shown. Incidentally these are the tools used for the experiment described in connection with Fig. 150. The die-holder is of interest in its construction. The draw ring is a chrome nickel cast iron with high wearing qualities but low tensile strength. It is held tightly in the holder by the tapered cast-iron ring. The holder itself is also of cast iron but with a steel

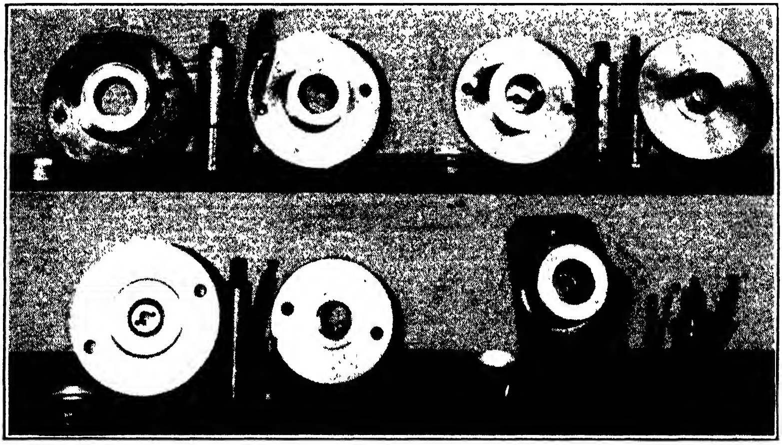


FIG. 172.—Dies to blank and draw, redraw, redraw and stamp a tapered shell.

band or ring shrunk around it to prevent any expansion while drawing, which might crack the draw ring.

Fig. 172 shows a series of four dies used in producing a tapered shell. The first (upper left) is a combination double-action die for cutting the blank and drawing to the diameter of the largest step. The next two dies (upper right and lower left) are double-action redraw dies with bottom lift-out pads. The last is a single-action die to stamp or stretch the steps out. These steps must be planned and developed with care to fill out with a little stretching into the final shape. An effort to draw this shell in one operation, granting that the reduction is not too great, would result in a series of lengthwise wrinkles which could not be stamped out.

Corrugations such as are shown in Fig. 167 may sometimes prove

troublesome. It will be noted that the metal has pulled in considerably at each side of the blank. Yet even this is not enough to furnish the total increase in surface. The balance must be made up by stretching the metal, the limit of which is its general elongation, Fig. 19. If there are several corrugations together, the stretching is likely not to be uniform, but to be localized on the inner corrugations. Free metal pulls in to the outside corrugations but is locked there preventing further travel. For this reason some jobs are arranged in two operations so that the center corrugations are drawn first and then those on the outside.

Multiple Operation Drawing.—Combination dies, which have been discussed, bring together a blanking, a drawing and possibly a stamping operation. Triple-action dies bring together two drawing operations, usually draw and redraw. Each of these may be limit operations, figured separately, provided the metal will stand so much cold-working without annealing.

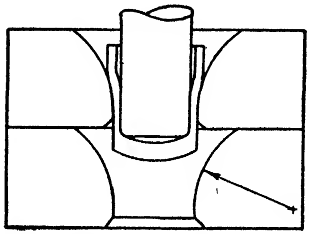


FIG. 173.—A typical two-step die for ironing cartridge-case walls.

Two-step reducing or ironing jobs (Fig. 148 *E*), in single-action tools, seem to be governed by the limits of single operations. They have some advantage, however, in the matter of wrinkles and of holding a size by localizing the principal wear on the first step. The latter advantage applies particularly to two-step ironing dies, Fig. 173.

A sequence of drawing operations may be combined in one automatic handling, with or without other types of operations. The limit upon the number of reductions combined is the amount of cold-working that the metal will stand without intermediate annealing. Alternative methods of doing this include keeping the part attached to the strip until finished, or feeding individual parts from station to station through the series of operations.

Fig. 174 *a* illustrates a typical series of operations of the so-called "eyelet" class. The shell, which is ordinarily quite small, remains wholly attached until completed and is then blanked out, or sheared off, as in the case of the radiation fin shown. For such work the typical first-, or first- and second-operation shells are dome or cone shaped, and the margin of the strip may show wrinkling and steps, unless the first dome can be obtained principally by stretching, as the tools are ordinarily of the single-action type. Piercing, curling, stamping and ironing operations are frequently combined in the series. The second station in the die is usually idle so that the first-operation dome may be used for locating and holding the strip.

Fig. 174 *b* shows the alternative method of follow-die drawing in which a preliminary piercing operation separates the strip into a series

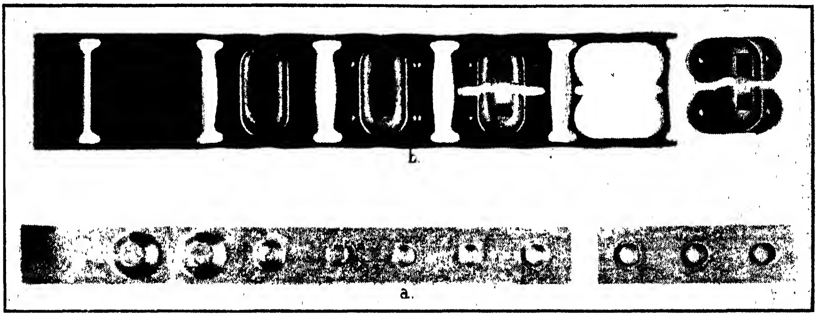


FIG. 174.—An eyelet type job (*a*), and a drawing follow-die job (*b*), in each of which other operations are combined with drawing.

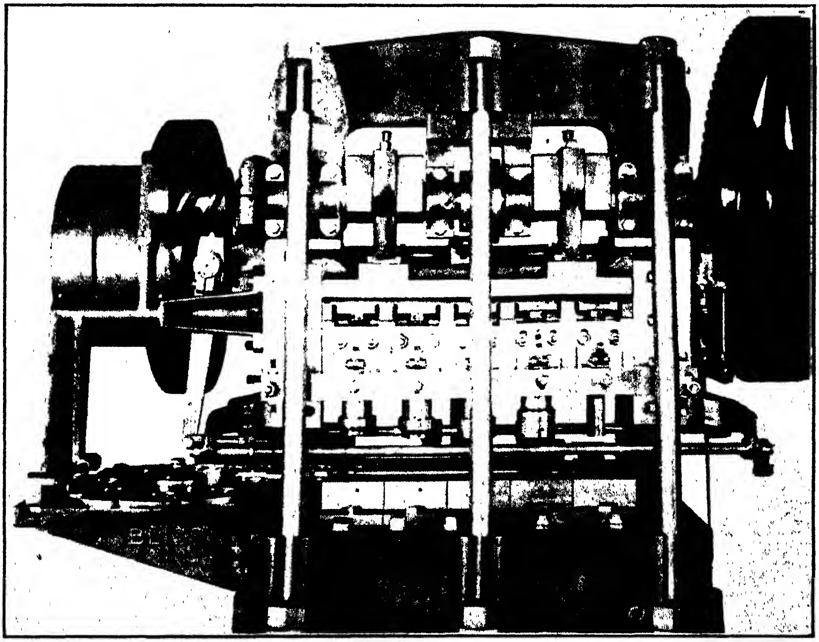


FIG. 175.—A series including drawing, redrawing, redrawing, perforating and trimming operations which is typical of many larger and smaller "multiple operation" groupings.

of blanks attached at each side to narrow bands of scrap. Then the drawing proceeds in the usual single-action dies, or air, rubber or spring

type double-action dies. In this process the original width of the strip is reduced but the center distance between tools remains practically constant. Other types of operation may also be combined in a series of this sort.

In either case, stripping and the disposal of scrap must be positive and reliable. The strip carrying the entire series of operations is raised and lowered every stroke and therefore must not be too flimsy or be subject to severe whipping. Automatic feeds must be accurate and carefully adjusted. Relative working levels in the tools during the several operations must be carefully planned to avoid distortion.

Fig. 175 illustrates the combined use of a series of separate tools with separate adjustments, the work being carried automatically from station to station. This method is applied to a wide range of work extending up to quite large-sized parts. The shape and the amount of cold working are its principal limitations. In many cases, strip or coil material is carried in by a roll feed and the first operation is blanking, possibly with a bridge die. More often, however, the first-operation shell is blanked, drawn and possibly annealed in a separate automatic unit and then fed into a " multiple slide press " by means of a friction dial feed. Such units also employ suction strip feeds, ratchet dials and magazine feeds as required. Ratchet dial feeds, alone, are sometimes used for a series of drawing operations but are generally inadvisable for more than a single operation. This is usually not the fault of the feed but of the lack of separate slide adjustment for the individual tools, or of difficulty in accurately centering varying shell diameters.

CHAPTER IX

DRAWING SPEED, LUBRICATION, ANNEALING

PRECEDING chapters have been devoted to the structure of metal, the manner in which ductile metal may be cold-worked and rearranged, the strain-hardening of the metal which results from cold-working, the removal of strain-hardening effects by annealing or recrystallization, selection of material, limits upon operations and finally details of drawing operations and tools. The following will conclude the discussion of the drawing group, covering something of the operating end.

Drawing Speeds.—How fast can metal be drawn? Figures available indicate a considerable divergence of opinion and a possibility of limiting speeds considerably in excess of common press practice. Copper wire is drawn at speeds as high as 2500 to 3500 ft. per min. Wire drawing appears closely analogous to the press operations of ironing or burnishing, yet 35 to 70 ft. per min. seem representative press-crankpin velocities for such jobs. Unrestrained drawing appears to be relatively easier than ironing, for we have reported drawing speeds of 200 ft. per min. for brass. It is probable that this applies particularly to single-action operations, for reasons to be pointed out.

In working steel all figures are lower and the situation is complicated by the tendency of particles of the metal being drawn to "pick up" or weld onto the die ring, causing scratches. Steel on steel makes a notably poorer bearing in machine construction than steel on a suitable dissimilar metal. A possible explanation, in both cases, is that the crystalline structure or lattice of both parts (the die and the blank) is exactly the same. Then when crystal fragments of identical orientation, but in the opposing surfaces, come together intimately under pressure, welding occurs, as the atomic attraction in a common orientation should be stronger than that between associated crystals of miscellaneous orientation.

Cold-drawn steel rod is drawn in chilled iron dies at 250 ft. per min. Yet a concern doing work of that sort reports that 26 ft. per min. is a maximum for burnishing steel in a punch press. Free press drawing operations in steel are reported at speeds of 35 to 60 ft. per min. Above 50 or 60 ft. per min. the danger of picking up seems to be great.

Occasionally when shells tear in drawing and the tearing is corrected by slowing the press down, the blanket conclusion is drawn that the metal will not stand working at such a speed. As a matter of fact, it has been shown that the per cent general elongation of steel (cold) increases with the speed of the test, at least up to the speed of a gunpowder explosion.

It is rather a case of inertia, mass times acceleration, or specifically, a sudden start as the punch hits the blank at midstroke with a high resistance to starting the metal made up perhaps of too severe a draw, too sharp corners on the punch and draw die and too high an initial blank-holding pressure. The compressive resistance to drawing set up in the flange of the shell is not any greater because of the greater speed. But with a given starting resistance, an increase in the suddenness with which the metal is started moving should increase the tensile strain on the metal around the nose of the punch.

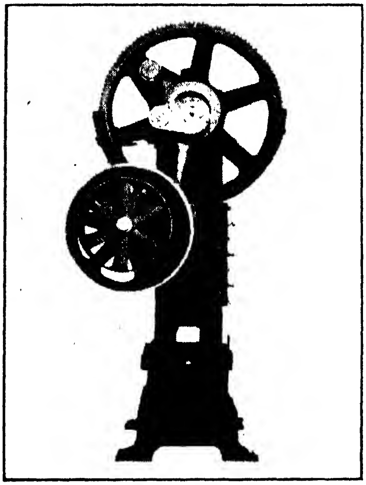


FIG. 176.—A press drive which materially increases the number of strokes per minute without increasing the working speed, for drawing, broaching ironing, etc. (patented).

Referring back to Fig. 148, note that the shell will start flowing more easily from under the angular blank-holder in die *B*, than it will with the flat blank-holder in die *A*. And obviously the absence of any blank-holder (single-action reducing), in case *D*, makes for far easier starting. The use of a large radius or angle on the nose of the drawing punch contributes to making the application of the load smoother and more gradual. The uniform stroke or " slow-draw " drive, Fig. 176, also contributes to easing the starting shock, or to speeding up the operation without increased shock.

A nomogram, Chart XII, is given in the Appendix for convenience in computing quickly the velocity of the press crankpin (V, feet per minute) for any given stroke (d, inches) and speed (RPM). Speed is taken in strokes per minute, with the press running continuously. The formula, which applies also to the peripheral velocities of flywheels and pulleys (belts), is:

$$V = \pi \times d \times \text{RPM}/12 \quad (34)$$

The velocity of the press slide (and the punch) is the same as the crankpin velocity only at midstroke, but the difference between them is not great until near bottom stroke. Fig. 177 is arranged as a means of comparing the relationship. In most drawing operations the punch strikes the metal at about midstroke. In very few cases does the draw begin lower than the last quarter of the down stroke, and it will be noted that even there the punch velocity is about 87 per cent of the crankpin velocity. Accordingly, crankpin velocities read from the nomogram, Chart XII, are sufficiently close to initial drawing velocities to require no correction for stroke position in most cases.

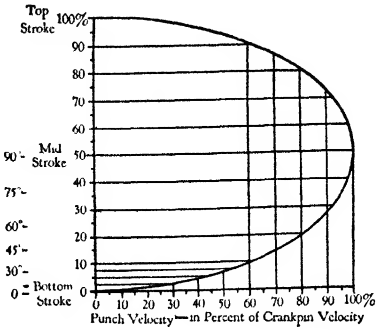


FIG. 177.—The relation between crankpin velocity and punch velocity at any point in the stroke.

If an accurate value is required for the velocity of the punch upon striking the blank, it may be obtained by Chart XIII, or the formula:

$$V = 0.5233 \times \text{SPM} \times \sqrt{dy - y^2} \qquad (35)$$

in which V is contact velocity in feet per minute;
SPM is strokes per minute;
d is press stroke in inches;
y is the position of the contact point in inches up from bottom stroke.

Table XVI is offered tentatively as a means of planning and of checking up existing practice. It is based upon the use of hardened-steel dies. The double-action column must be qualified according to how securely the metal is gripped at the beginning of the draw.

It is of interest to note that one well-known concern purchases copper-plated drawing steel to speed up drawing operations and eliminate "picking up" on the dies. The practice seems logical and may be further warranted by subsequent plating of the parts.

Chrome plating of dies for drawing steel shells (and also for other work) has been reported as extremely satisfactory by some companies, but others had trouble in getting a good plating job on the inner surfaces. Some companies use a very hard cast aluminum-bronze for drawing dies for steel, aluminum and stainless steel. Here again, in principle, the provision of a dissimilar metal for the steel to slide against should permit speeding up the operation materially.

TABLE XVI

TENTATIVE TABLE OF LINEAL VELOCITIES

	Drawing		Ironing or Burnishing, Feet per Minute
	Single-Action, Ft./Min.	Double-Action, Ft./Min.	
Steel	55	35–50	25
Steel (in carbide dies)		60	
Brass	200	100	70
Copper	150	85	
Aluminum	175	100	
Strong aluminum alloys		30–40	
Zinc	150	40	
Stainless steel		20–30	

Lubrication in Drawing.—Practice in the use of lubricants on drawing operations seems to be directed to a considerable extent by individual taste. Some general statements can be made, however.

Often a film of oil is essential on bright stock to protect it in storage. Oil lends itself to automatic lubrication by spray or drip and wiper, and often one application is enough for several operations. Usually an ordinary mineral oil is satisfactory. As drawing conditions become more severe a compounded oil including say 15 per cent of lard oil and 5 per cent of wool fat in a mineral-oil base is about as efficient as pure lard oil and much less expensive. Occasionally an unusually heavy job is considered to require heavy, crude oils which are very sticky and messy. White lead has come into disrepute on account of possible lead poisoning. Graphite is mixed up with oil or with kerosene for some heavy operations but must be kept in suspension.

Electrical lamination steel is often lubricated with paraffine applied warm to the sheets. A mixture of paraffine oil and kerosene applied sparingly, to evaporate in process, is also used.

Oil lubricants are common but ordinarily have to be cleaned off before annealing to prevent the oil burning into the steel. They must also be carefully cleaned off prior to soldering or to applying many finishes.

For such reasons, water-soluble lubricants are widely used. These include soap solutions, flour, sulphonated oils, talc, amorphous chalk, zinc oxides, etc., in various mixtures which are more or less stable. Warm soapsuds are recommended in drawing zinc, the warmth raising the temperature of the metal slightly to improve its ductility.

[1] "Principles of Lubrication in Cold Drawing Sheet Steel," by H. A. Montgomery,

The water-soluble lubricants usually have to be applied quite freely, as by dipping the strip or part in a tank of lubricant, Fig. 1. A paint brush or a rag swab, Fig. 179, are common to both oil and water lubricants. The efforts of the helper in Fig. 179 seem extravagantly

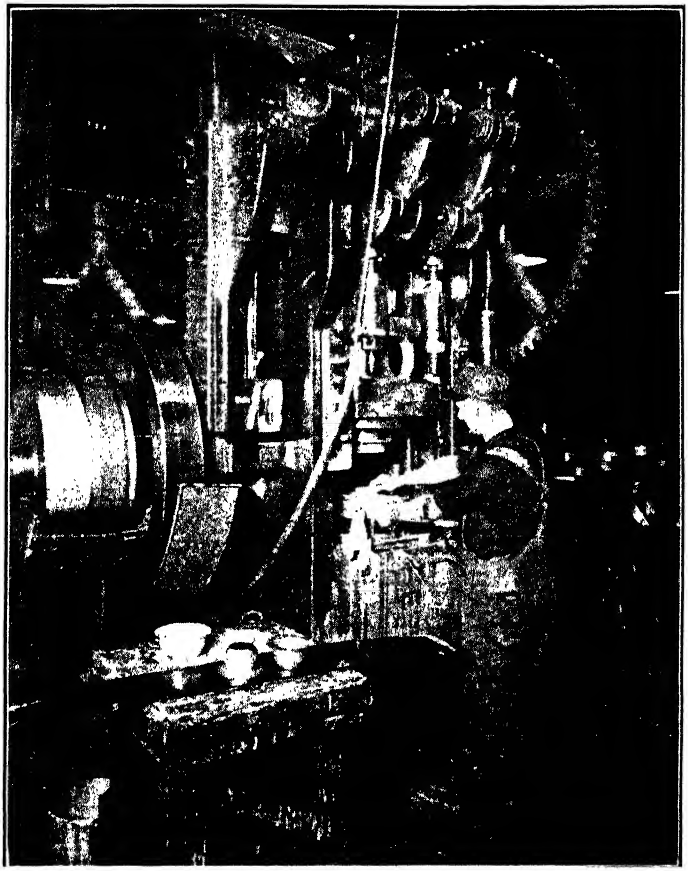


FIG. 178.—Drawing universal joint covers in a toggle drawing press with a soluble talc base lubricant.

careful, however. Simple atomizer sprays attached to the press and operated by mechanically or hand-controlled air jets are a natural solution for quantity production. Fully automatic roll feed presses are frequently fitted with drip valves and felt rolls or wipers to spread the lubricant.

Annealing.—Annealing is the process of restoring a structure consisting of relatively large, unstrained crystals to metal which has been

structurally strained and distorted by the slip-plane movements of severe cold-working.

Quite generally accepted hypotheses enable us to draw a fairly complete detailed picture of the process. Parts of this have been more fully covered elsewhere.

The starting point is the atom, which is the elementary unit distinctive to any metal (or other element). Because of their own structure and resultant directional forces of repulsion and attraction, the atoms of any metal tend to arrange themselves, with respect to each other, in certain definite crystalline patterns. Cold-working of the frozen crystals twists the atoms which form a given crystal out of their natural equilibrium positions and destroys the continuity of the crystal.

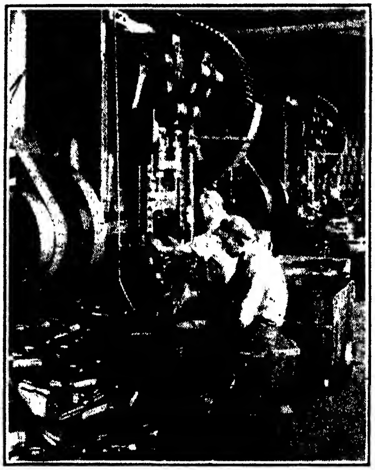


Fig. 179.—Expensive application of expensive (lard) oil for a drawing operation in 0.049-in. hot-rolled steel on a toggle press.

The application of heat increases the activity of the electrons forming the atom and therefore increases the energy of the atom and the forces which it exerts. When the temperature is raised to the annealing or recrystallization point the atom is enabled to rotate itself into an easier and less strained position relative to its associates. The easiest relation is of course the space lattice of the unstrained crystal, and it is to that spacing and directional arrangement that the atoms tend to return. The more time at heat and the higher the heat, the easier it is for the normal crystalline structure to develop.

It may be noted that continued application of heat continues to increase the activity in the atom and the space between atoms in the crystal lattice (expansion of metal) up to the melting point, where the crystalline relation disappears entirely.

Fig. 180[2] illustrates clearly the effect of the annealing process upon the crystal structure. At 75 magnifications a polished and etched specimen of severely cold-worked brass at *A* appears to have retained the outlines of the original large crystals, elongated or distorted, however, by the working. Upon the application of heat, raising the metal

[2] Jeffries and Archer, "The Science of Metals," McGraw-Hill Book Co., New York, 1924, and the American Brass Company, Waterbury, Conn.

FIG. 180.—Brass, 68 : 32, cold-rolled from soft temper, 50.9 per cent reduction, to extra hard temper (at *A*); next heated for recrystallization at 300° C. (*B*) and 350° C. (*C*); followed by grain growth during annealing at 450° (*D*), 550° (*E*), 650° (*F*), 750°(*G*), 850° C. (*H*). ×75 (Bassett and Davis).

to its recrystallization range of temperature (at *B* and *C*), the old grain boundaries rapidly disappear and the equilibrium condition develops as a great many very small grains or crystals. With continued increase in temperature the average grain size increases perhaps twenty fold (Fig. 180 *D* to *H*) as atoms of the smaller crystals realign themselves with larger and more powerful adjacent crystal structures.

Fig. 180 parallels closely the first part of the plastic cycle as charted in Fig. 127. There recrystallization is marked by the sharp drop in tensile strength and the appearance of the new small grains. Grain growth in Fig. 127 was stopped at "soft temper" corresponding approximately to Fig. 180 *F* and the initial state of Fig. 180 *A before* it was cold-worked. In Fig. 180 (*G* and *H*), grain growth was carried on considerably farther than in Fig. 127 with a proportionate increase in ductility (elongation) and decrease in resistance to working. Grain size and temperature cannot be compared precisely in Figs. 127 and 180, owing to differences in initial cold-working, composition and annealing time.

These two illustrations indicate the possibilities of so controlling grain size in annealing as to retain a greater or less amount of stiffness in the finished product while eliminating internal strain by going beyond the recrystallization temperature. Thus in Fig. 155 *D* a cartridge case is annealed to a smaller grain size than in its previous operation in order to retain some stiffness in the neck. The anneal was carried out in 7 to 8 minutes at 1300° F., which compares, in the physical properties obtained, with, say, a 30-minute anneal at 600 or 700° F. in Fig. 127.

Discussing the effect of grain size upon physical properties in the unstrained state, Templin [3] said, "In the absence of cold-work, the grain size of a metal becomes of considerable importance. Experimentally it has been demonstrated that a piece of commercially pure aluminum sheet could be cut in half and each half annealed so as to produce in one a very fine-grained structure and in the other a very coarse-grained structure; with the result that the fine-grained piece has a tensile strength about 40 per cent greater than the coarse-grained piece."

Jeffries and Archer [2] have very logically explained the higher strength accompanying smaller crystal size as being due to more frequent boundary interferences. Plastic working takes place by separate slip-plane movements traversing unobstructed planes of weakness between rows of atoms through favorably oriented crystals along its path. Thus, in such a fine-grained structure as is illustrated in Fig. 180 *D*, each individual slip movement could progress only a very short

[3] R. L. Templin, "Effects of Cold Working on Physical Properties of Metals," Technical Publication 238, A.I.M.M.E.

distance before being stopped by a maze of random atoms at a grain boundary. By the same token a lower yield point in the structure at Fig. 180 *H* and a possible zero yield point in the single crystal state are the natural results of the greater freedom of movement without boundary interference.

Returning to annealing practice, many factors will affect the temperature at which work-strained metal begins to recrystallize. Table XII in Chapter VII gave approximate minimum temperatures at which this process starts in various metals under favorable conditions. Annealing requirements and results are affected by:

(1) the amount the metal has been cold-worked;
(2) the temperature at which it was worked;
(3) its condition (grain size) before cold-working;
(4) the presence of impurity or alloying elements;
(5) the state during annealing (sheets, packs, coils, stampings);
(6) the length of annealing time;
(7) the temperature of the anneal;
(8) the ultimate grain size desired.

(1) Severely cold-worked material can be completely reannealed at a lower temperature than metal only slightly strained. This is probably due to the greater tendency toward rearrangement of the former and the smaller fragments on which to build. Drawn shells are of interest in that the metal around the wall is severely worked at the top edge but has received less and less working down to the bottom, which is practically unstrained.

(2) The rate at which metal strain-hardens in cold-working is less rapid as the working temperature approaches that of recrystallization. It is occasionally found that shells being worked to the limit will show a lower percentage of breakage in the summer than in the winter. Also, it is claimed that combinations of redrawing operations, as in double draw dies, permit greater reductions because the second operation is started while the metal is still warm from being worked in the first operation. The advantage is probably relatively small for steel because the temperature difference is not great (probably not over 100° F.). For similar reasons, advantage is claimed in using heated dies. This, again, would be most likely to show where considerable breakage results from excessive working between anneals for the metal used.

(3) Strain-hardening in the cold-work range is necessarily cumulative. Suitable metal which has not been thoroughly annealed and then perhaps has been subject to appreciable cold-rolling is not in its best state for reductions in drawing. Cold-rolling is of course cold-working.

This does not reflect upon cold-rolled drawing steels, which had to be capable of withstanding considerable cold-working to be produced by that process, providing they have not been subjected to excessive reductions (causing fractures) in the process, and providing they have been thoroughly annealed after rolling. To obtain a highly finished surface, it is necessary to subject the metal (annealed at relatively low temperature) to a final light pass of cold-rolling with polished rolls. This must

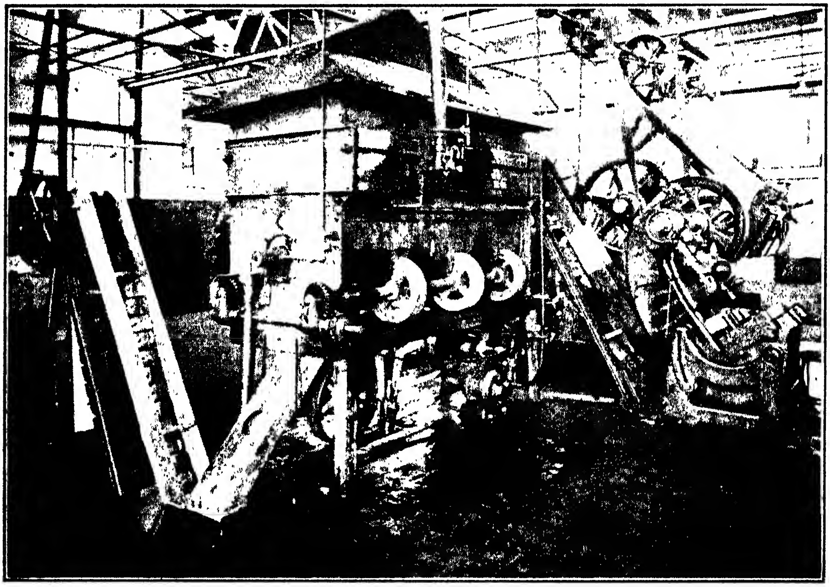


FIG. 181.—An automatic annealing equipment for drawn shells hooked up with the presses for operations both before and after the anneal.

cause a proportionate small amount of strain-hardening which cannot be removed.

(4) The presence of impurity and alloying elements in pure metals tends to increase both the annealing temperature and the frequency of annealing. It was shown, for example, in Fig. 31 that the rate of strain-hardening of steel is more rapid as the carbon content increases. Increasing percentages of phosphorus, manganese and silicon in steel also increase the strain-hardening rate and therefore the frequency of annealing. It is said that 0.02 C wire may be satisfactorily annealed at 700° C., whereas 0.12 C wire annealed at 720° still shows cementite (Fe_3C) in elongated strings damaging to the structure.

(5) In general, coil stock has a better reputation for drawing quality than sheet or strip material, apparently because the latter is usually

annealed in large packs requiring relatively long heating at low temperatures with non-uniform results. This is overcome, as in the case of many automobile sheets, by separate annealing of sheets in special automatic ovens. Drawn parts are usually annealed either in conveyor or rotary-type ovens, Fig. 181, in which they are easily reached by the heat, and then are carried out and cooled quickly.

(6) Slow annealing is unavoidable if a large mass must be penetrated. The longer the anneal at any given temperature the greater is the average grain size and the possibility of non-uniform excessive grain growth in favorable localities. Rapid annealing involves higher temperatures, and with the thin uniform sections of stampings, the penetration is immediate, and recrystallization starts simultaneously from many points with a uniform resultant structure.

(7, 8) For the same length of time in annealing, a higher temperature will result in the growth of larger grains. Or if a smaller grain size is desired, a shorter exposure or lower temperature will be required.

It has also been shown that in drawing steels having a carbon content between 0.02 and 0.12, and in some other metals, there is a critical combination of strain and temperature at which " germination " or an excessive grain growth results. For any given condition of strain there is no grain growth below this *critical temperature* and only moderate or normal grain growth above it. The variation of strain and temperature follows the same lines as the more general recrystallization temperature. That is, more severely cold-worked material has a lower germinating temperature than that which is less severely worked.

It has been noted that the severity of strain in the side-wall of a drawn shell varies from zero at the bottom to a maximum at the top edge. Accordingly, a 0.08 C shell might be annealed at a temperature which would produce germination say half way up the shell wall. There would then be a band of excessively large and soft grains about the center of the shell shading into normal annealing above and an unannealed state below. Such a condition would be likely to result in tearing at the weak band in further reductions.

Table XVII, showing experimental results obtained by Ruder,[2] illustrates the variation of the point of germination with strain and temperature in silicon steel. When the metal is heated fairly quickly through the germinating temperature there is not time for excessive grain growth.

By way of illustration of commercial annealing practice, one well-known manufacturer issues the following blanket instructions for the annealing of stampings made of " deep drawing " steel, in preparation

[2] See footnote, p. 198.

for further redrawing. "Previous to annealing all oil must be washed off in a 10 per cent caustic solution. Then the parts must be dipped in a lime solution kept at about 180° F. When dry they are placed in a furnace at about 1250 to 1300° F. and kept there for about a half hour or long enough to insure thorough penetration. The parts are then cooled relatively slowly in another chamber." Another manufacturer, using a rotary-type annealing furnace, maintains a somewhat higher temperature, heats for perhaps 10 minutes and then cools in air.

TABLE XVII

GERMINATION AND NORMAL GRAIN GROWTH IN SILICON STEEL [2]

Per Cent Cold-Working	Ten-hour Anneal at Fahrenheit Temperature (Degrees) of			
	1380	1470	1740	2000
0.625	0	0	0	Coarsest
1.250	0	0	Coarse	Normal
2.500	0	Coarse	Normal	Normal
5.000	Coarse	Normal	Normal	Normal
6.750	Normal	Normal	Normal	Normal

Strains and Surface Markings.—Considerable space has been devoted to metal movement in drawing, showing, as in Figs. 117, 140 and 149, how the metal is crushed into a smaller and smaller circumference with proportionate strain-hardening. In rectangular shells this action is localized largely in the corners; in almost every case the severest compressive action is around the top edge or flange of the shell and the severest tensile stress is above the bottom radius in the side-wall. In proportion to the severe cold-working involved, the crystalline structure of the metal is severely crushed out of shape, necessarily leaving a network of strains throughout with actual minute fractures in places if the work has been carried too far.

A number of distinctly different markings on the outer surface are recognizable, indicating what has been done to drawn shells. On the upper part of the shell wall, where high compressive stresses have been experienced, there may be a uniform unmarked surface possibly with a polished line around the top edge, a uniform polished surface, vertical scratches, vertical bands alternately polished and dull, or vertical cracks starting down from the top edge. On the lower part of the shell wall,

[2] See footnote, p. 198.

where the high tensile stress has been experienced, the surface may show no markings, or a dull, pebbled appearance due to many little humps,[4] or many small, horizontal, straight or crescent cracks, or horizontal fractures or tears. On the bottom of the shell the surface may be unmarked or show burnished portions or an alligator-skin pattern of wavy strain markings.

Some of the shells in Fig. 136 have a narrow polished line around the top edge. Otherwise they are unmarked as the draw was not severe and there was ample clearance between punch and die for the normal increase in wall thickness. The line is due to the stiffness of the curl around the top edge of the shell left by the drawing radius. The line may be reduced somewhat by increasing the draw radius, though with increased danger of wrinkles.

A burnished or polished surface indicates ironing. If the polish extends only part way down the shell, the clearance between punch and die is probably about equal to the original metal thickness, and the ironing is merely removal of natural thickening in the upper wall (Fig. 149). Ironing to remove pits due to pickling or tumbling or to burnish the whole length of the side requires a die clearance considerably less than the original metal thickness. Ironing will burnish over surface cracks but will not remove the weakening effect of their presence.

Vertical surface scratches indicate that metal has picked up or welded on the drawing radius. The cure may be merely repolishing the radius, possibly polishing in the direction of metal flow (for foil, etc.), using a harder ring or a better lubricant, or slowing the press down.

Vertical bands, alternately polished and dull, indicate that wrinkles have formed and have been partially ironed out. It is rarely possible to iron them out completely, and in any case the wall has been weakened at the fold or corner of the wrinkle. (See Fig. 140 *e*.) The cause may be insufficient blank-holding pressure, too much draw radius, too little corner radius (rectangular shells), etc.

Frequently vertical cracks start down from the raw top edge of the shell if the particular metal is being cold-worked excessively between anneals. The cure is usually more frequent annealing, less severe reduction or better material. If the cracks do not appear for hours or weeks after drawing, the phenomenon is called "season cracking." The causes are the same, but the action may be aggravated by the presence of a little unremoved pickling acid. This acid, particularly in a moist atmosphere, is said to react to free hydrogen which is absorbed by the metal and seems to lower the cohesive strength along the grain boundaries and make the metal brittle. Typical "season cracking"

[4] "The Importance of Grain Size of Sheet Steel for Deep Drawing," by Reid L. Kenyon, 1934, A.S.M. preprint.

resembles the gradually spreading intercrystalline fracture of a fatigue break. See Fig. 139.

With a relatively large bottom radius on the drawing punch, an easy draw, annealed drawing material and ample clearance, the lower part of the shell is likely to show very little marking.

Frequently, however, the metal will show evidence of the working it has undergone, although no real damage has been done to it. Bright finished stock will, after drawing, present a dull finish which, under small magnification, gives the appearance of a pebbled surface or a series of tiny bumps. The relatively limited internal movement in the metal has apparently been sufficient to cause a twisting of groups of crystals through slip-plane movements, ruffling the previously smooth surface. The coarseness of the pebbling is reported to be proportionate to the grain size.

The next severer stage is a development of the same pebbled surface, in the area of high tensile strain, to a point where a multitude of tiny surface cracks, principally horizontal, begin to appear, under small magnification. If the metal is amply ductile this condition is likely to be accompanied by thinning or necking of the shell wall a little above the bottom radius, with occasional failures by tearing the bottom out of the shell. The cause of the trouble may be that strain-hardened material in the upper wall is offering too much resistance and better annealing is required, or that the reduction per draw is too great for the plasticity of the material, or that the punch radius is too small.

A burnished line around the shell just above the bottom radius indicates a relatively small bottom radius on the drawing punch in relation to the metal thickness.

Highly finished deep drawing steel in particular is likely to show strain markings on the bottom of the shell, which may also be described as phantom lines or alligator-skin markings. Such lines may also appear, and detrimentally, on shallow form jobs where the blank must be stretched to shape as in Fig. 142. The Bureau of Standards[5] has demonstrated that these markings are due to "deformation by slip within certain favorably oriented grains," and are the result of "extremely slight deformation" at or slightly above the yield point of the material. In a drawn shell the damage is probably done just at the beginning of the draw. It is claimed in automobile work that the effect is eliminated by running the sheets through a roller leveler immediately before drawing. The leveler should effect slight strain-hardening.

Burnished portions on the outside of the shell bottom indicate coin-

[5] Research Paper 15.

ing of the metal in hit-home dies, a dangerous practice for the press if care is not exercised.

"Ears" on Drawn Shells.—The formation of "ears" or high points around the top edge of a drawn shell is the result of directional differences in the plastic-working properties of rolled metal with, across and at 45° to the direction of rolling. In the case of metals which are free from foreign inclusions these directional differences are supposed to be removed by annealing after rolling.

Fig. 25 and Tables VII and VIII show, in shearing, tensile and bending tests respectively, the directional differences in metal which result from cold rolling without correction by annealing. Fig. 25 *B* and *C* show that the old grains are much elongated in the direction of rolling. All three tests indicate that the metal has been strain-hardened less and has a lower yield point and greater plasticity in the direction of rolling than it has perpendicular to the direction of rolling. That is, for greatest structural strength a specimen should have its stress axis across the direction of (cold) rolling. But for further cold-working with least likelihood of fracture the direction of the stress should parallel the direction of rolling.

In a homogeneous metal there should be nothing to prevent the normal grain growth which follows recrystallization, from proceeding uniformly in all directions. Such growth should produce substantially equiaxed crystals which would retain practically none of the directional differences produced by cold-rolling. Within certain limits of cold-rolling and annealing temperature, this seems to be the case. But (in brass and pure copper, for example) it seems possible by critical combinations of high annealing temperatures and severe reductions to produce metal which will form objectionable ears or high points upon drawing.

Templin [3] claims that an initially fine-grained metal is less likely to show directional properties after severe cold-working and then annealing, than a coarse-grained sample treated in a similar manner. Phillips and Bunn [6] add their belief that " extremely heavy reductions (in rolling) are to be avoided if uniform mechanical properties are desired." In an earlier research, Phillips and Edmunds [7] described a comparison of two samples of copper only one of which formed objectionable ears or tips upon drawing. The satisfactory sample, cold-rolled in a number of passes, was reduced 77.5 and 70 per cent with intermediate and final

[6] A. Phillips and E. S. Bunn, "Directional Properties in Rolled and Annealed Copper," Technical Publication 413, Institute of Metals 132, A.I.M.M.E.

[7] A. Phillips and G. Edmunds, "An X-ray Study of Copper Which Showed Directional Properties on Cupping," Proc. A.S.T.M. (1929), 29, Pt. II, 438.

anneals at 1120° F. and showed an equiaxed grain structure. The unsatisfactory sample was reduced 74 per cent in both steps between annealings and showed some grains in its final structure which were elongated in the direction of rolling. X-ray analysis of the crystal-plane structure was reported to show distinct directional preferences in the case of the metal which formed ears, compared with uniformity of crystal structure in the other case.

The reductions described would seem to indicate that this metal had been worked close to its plastic limit, and that possibly groups of favorably oriented slip planes had suffered an over-strain or layer separation which would remain after annealing to interfere with uniform grain growth.

Physical Test Data.—The physical tests which are in use for judging the drawing properties of metals include particularly cupping tests, the standard tensile test and microscopic examination. Their object is to discover the initial condition and to measure the workability or plastic range of the metal.

Microscopic examination of a polished and etched section may reveal to the experienced eye about as much as any test, for drawing purposes. It will show, for example, whether the grains are strained or relatively unstrained, or whether they are small, large or unduly non-uniform. In steel, one may judge the proportion of the light-colored and ductile ferrite crystals to the dark and less ductile pearlite; in brass, judge the presence of unabsorbed zinc or lead at the grain boundaries which weakens the structure for drawing. In copper, fine particles of copper oxide diffused through the crystals harden the material by interference with the slip-plane movement in cold-working, etc.

Cupping tests endeavor to imitate the drawing operation and offer a means of comparison of some properties which are of interest. Here a blank or strip sample is clamped upon a small round die by means of a blank-holder ring, and a round-nosed punch is then forced against the blank, drawing it down to the breaking point, Fig. 182. The distance the punch has penetrated at fracture is taken to indicate the relative drawing capacity. The appearance of the break and of the surface of the severely stressed metal serves to indicate grain size and uniformity of structure in a general way.

This test indicates the ductility of the metal, as most of the deformation is obtained by stretching, although stretching plays little part in drawing shells, as was shown in Chapter VIII. It does not ordinarily test malleability, as required for the compressive movement in most drawing operations. And as indicated in Table XI, ductility and malleability are not quite the same thing.

Furthermore, the cupping test is performed slowly compared with press operating conditions. It is essentially a test of general elongation which changes with speed, for, to quote Maitland, a steel which showed 27 per cent elongation in 2 in. when broken slowly, showed 47 per cent elongation when broken by the inertia of a falling block, and 62 per cent elongation when broken by a gunpowder explosion—and even this is well below the ultimate elongation, Figs. 19 and 126. The per cent elongation in 2 in. (or any appreciable length) is *not* an index to the maximum amount which the metal can really be moved in tension, but merely indicates at what point that elongation becomes local instead of general, or how soon "necking" occurs under the specific conditions. Local weaknesses in the material which cause necking to start (often intercrystalline) require time to develop.

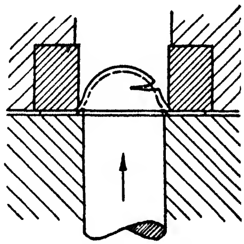


FIG. 182.—The cupping test for drawing properties of metals shows relative general elongation and type of fracture.

Further variation due to speed occurs in the cupping test with those metals which recrystallize near or below room temperature and therefore are worked in the "amorphous" condition. In this phase, speed of working is known to affect many properties. An investigation by Mathewson, Trewin and Finkeldey[8] reports regarding the cupping test that "the only means of obtaining reliable practical indications of the drawing quality of the material [zinc] is to deform the metal at a rate comparable with that which obtains in practice in actual press work." This is done in a dynamic testing unit comprised of a double-action cupping die in a bench press, with special screw adjustment for easy depth changes, Fig. 183.

The well-known tensile test has certain disadvantages, but may readily prove quite satisfactory as a means of determining the plastic range of a sample of metal for drawing purposes. It was pointed out, in connection with formula 23 and Figs. 17, 18 and 126, that per cent reduction in diameter is a proper measure of metal working in drawing, and that it is directly comparable with per cent reduction in area as measured in the tensile test. The reduction in area from the original cross-section to that at the neck when failure occurs, measures accurately the plastic range from whatever initial state the metal may be in, to the plastic limit at which all slip planes have been used up and failure follows. An initial state comprising a large-grained, unstrained struc-

[8] C. H. Mathewson, C. S. Trewin and W. H. Finkeldey, "Some Properties and Applications of Rolled Zinc Strip and Drawn Zinc Rod," Trans. A.I.M.M.E. (1920), 64, 305.

ture will extend the workable range, and a small-grained or partially cold-worked (strain-hardened) structure will of course reduce it.

Another method of determining the plastic workability might be offered for metals for which we may know the chemical analysis and corresponding plastic curve or rate of strain-hardening curve, Fig. 122. On such a curve the plastic limit, or the point to which plastic working

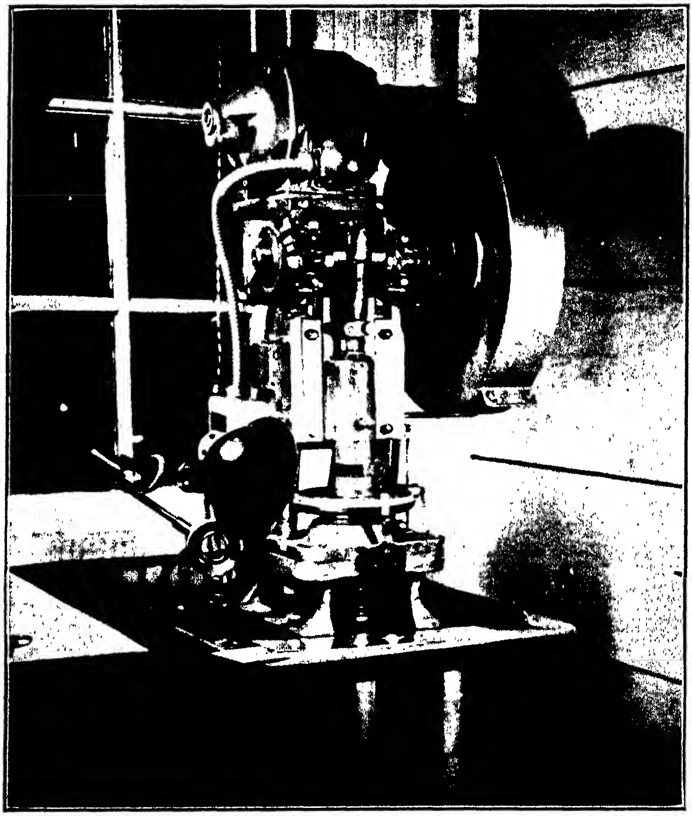


FIG. 183.—A dynamic ductility testing unit for performing the cupping test at normal drawing speeds.

may safely be carried, should be permanently designated. The initial theoretical yield point of the metal, as received, must then be found and noted on the curve to determine the extent to which the metal may safely be cold-worked. The vagaries of the initial yield point were illustrated in Figs. 118 and 123, showing test yield points above, below and on the plastic curve. It is therefore suggested that the theoretical yield point be determined by carrying the test a known amount beyond the

elastic limit to a point (S_2) safely upon the plastic curve and then figuring back the position of the theoretical initial yield point (S_1) by a modification of formula 17 (see also Fig. 125).

Thus, for example, we may measure the stress (actual unit stress, S_2) required to produce an elongation of, say, 25 per cent on a measured gauge length on the specimen, provided it is a sufficiently ductile metal so that the general elongation before necking begins is greater than this amount. By Fig. 18, 25 per cent elongation is equivalent to 20 per cent reduction ($r = 0.20$). We have assumed that S_x, the measure of the rate of strain hardening of the metal, is known. Then, by rearranging formula 17, the theoretical initial yield point should be:

$$S_1 = \frac{(S_2 - rS_x)}{(1 - r)} \tag{36}$$

The test elongation and corresponding value of r may of course be chosen to suit the metal.

CHAPTER X

COLD OPERATIONS OF THE SQUEEZING GROUP

SQUEEZING a slug or blank of metal to a desired shape by sheer force is the last and the most severe of the four groups of press operations. Included are the classes known as sizing, swaging, embossing, coining, extrusion, press forging and some stamping operations.

The pressure required to accomplish a squeezing operation depends upon the area squeezed, the extent of the squeeze and the resistance offered. This resistance varies with the metal, the freedom of flow and the amount the metal has been and is to be cold-worked.

It is useful to consider the metals which are worked by squeezing as very viscous fluids. For practical purposes they are incompressible, so that any squeeze in one direction must be expected to yield an expansion at some other point. In cold-working operations the " viscosity " increases as the movement progresses.

Volume Changes.—For close computations it may be noted that the volume of the whole piece or the density (mass per unit of volume) of parts of it are altered slightly by pressure, temperature and cold-working.

An increase in external pressure causes a very slight reduction in volume owing probably to elastic reduction of the distance between atom centers in the crystal structure. This may be approximated from the bulk (volume) modulus, Table XXVII. An elastic return to the original volume is to be anticipated upon relief from pressure. The ratio of unit pressure, S, to the bulk modulus, B, is the same as the ratio of the volume change, $(V_1 - V_2)$, to the (smaller) volume, V_2:

$$\frac{S}{B} = \frac{(V_1 - V_2)}{V_2} \tag{37}$$

Cold-working of a metal (below its recrystallization temperature) actually causes an increase in volume. The change is small, being in the nature of 0.3 per cent for extremely severe cold-working. The reason for it is undoubtedly that the badly distorted structure of the severely worked material keeps it from packing so closely as an unstrained crystal structure of uniformly spaced atoms permits, just as crushed stone

cannot be packed closely enough to equal the density of the solid rock. Accordingly, it may be anticipated that annealing or recrystallization which regenerates the grain structure will bring the density and volume

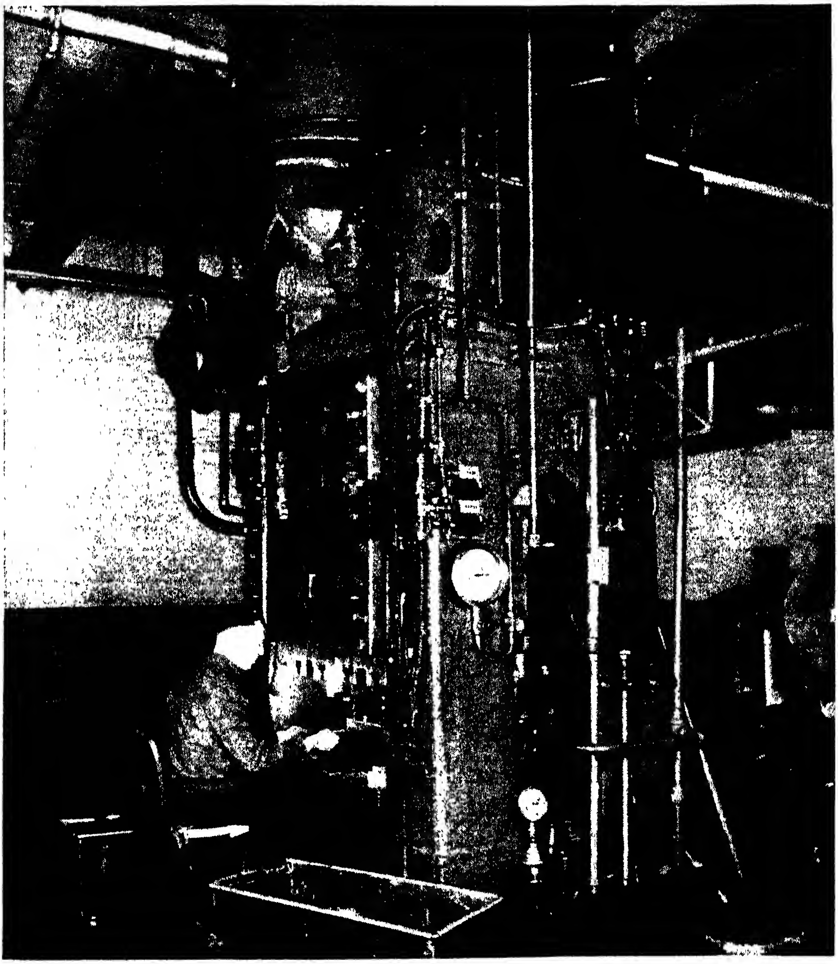


FIG. 183a.—1000-ton Bliss fast-acting hydraulic press stamping electric stove parts. This type of press gives controlled working pressures.

back to normal. Table XVIII, taken from the data submitted by Houdremont and Burklin in the *Iron and Steel World* for December, 1927, shows very well the decrease in density as a low-carbon steel wire is cold-worked by redrawing. See also the density curve, Fig. 124.

The application of heat also increases the volume of metals, owing, it is believed, to the increased period of vibration of the electrons and

hence the increased spacing of atoms in the normal crystal lattice. Allowance must therefore be made in the dimensions of dies for press forging and hot sizing for the amount the piece will shrink upon cooling. In general, any die dimension L_1 should be:

$$L_1 = Lf(t_1 - t_2) \tag{38}$$

in which L is the desired cold dimension of the piece, f is the thermal coefficient of linear expansion from Table XXVII and $(t_1 - t_2)$ represents the difference between the working heat of the piece and average room temperature in degrees Fahrenheit. When the dies are operated consistently at a fairly high temperature, a further correction may be made for that if so desired.

TABLE XVIII

DENSITY CHANGE WITH COLD WORKING[a]

Steel No. 1 Analysis	Wire Diameter, Inches	Reduction of Area, Per Cent	Tensile Strength, Pounds per Square Inch	Density	Density Decrease
0.13 C	0.315		59,800	7.858	
0.27 Si	0.232	45.3	98,200	7.846	0.15
0.48 Mn	0.139	80.5	114,000	7.832	0.33
0.026 P	0.083	93.1	158,000	7.829	0.37
0.021 S	0.032	98.92	216,000	7.813	0.55
	0.016	99.75	248,000	7.786	0.89
		Hardened at			
	0.315	1436° F.	107,000	7.840	0.14
		1688° F.	150,000	7.853	0.06

[a] From Houdremont and Burklin.

Pressure of Fluidity and Rate of Strain-Hardening.—Unwin has given what he calls a "pressure of fluidity" for copper at 54,000 lb. per sq. in. and for steel at 112,000 lb. per sq. in. Certain it is that metal is made to flow, cold, in many die operations. But its path through the tools and its previous treatment have much to do with the pressure required to start it. The extent of the flow may raise the pressure considerably higher during the operation because of strain-hardening.

According to Fig. 122, a commercially annealed mild steel (of say 0.15 C) will offer a resistance of about 56,000 lb. per sq. in. at its annealed yield point where "flow" really begins. If it is submitted to the tensile test, its resistance to flow (or stretch in this case) increases as it becomes longer until it fractures at an actual unit stress at the cross-section of the neck of around 110,000 lb. per sq. in. In Table XVIII a low-carbon steel has been cold-worked, by the more favorable process of wire drawing, to a point where it offers a resistance to further working of 248,000 lb. per sq. in. That might be considered the "fluidity" resistance of that particular piece of mild steel in that state of strain-hardness.

Fig. 14 showed how samples of different steels followed the same elastic curve up to different yield points according to their carbon content. Figs. 15, 118 and 184 show how the yield point of any metal rises as the metal is strain-hardened, whether that strain-hardening is accomplished by cold-rolling, cold-drawing or cold-squeezing. Figs. 16, 17, 120, etc., have been arranged to show that the metal behaves itself approximately in essentially the same way internally whether the direction of the deforming force is tensile or compressive. This is of value in that it permits determination by tensile test of the yield point of metal which is to be worked in compression. The cross-section area of the metal does not change appreciably in the elastic range, and directional load differences should not be of practical importance.

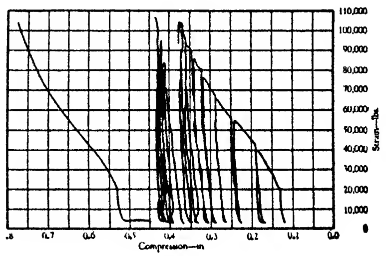


Fig. 184.—Compression-test curves, both continuous and interrupted, of alleged 0.15 C steel.

Yield point of the metal *as received* is emphasized with respect to squeezing operations because the metals used in this group are often purchased in quarter-hard or half-hard temper to avoid dragging down of high points, as in Figs. 193 and 207, by tensile surfaces stresses. Even when annealed metal is used it must be noted that commercial annealing rarely produces as low yield points as the laboratory values given, for example, in Fig. 19. To show the manner in which the yield point changes with cold-working and to show that steel behaves in essentially the same manner as the non-ferrous metals (Chapter VII), the experimental test curves shown in Fig. 184 were obtained and checked in an Olsen recording testing machine.

Two blanks or slugs ¾ in. in diameter and ½ in. high, out of the same piece of 0.15 C machine steel, were carefully annealed and allowed to cool in the furnace. One slug was compressed steadily to about half its original height, rising from a yield point, in the annealed state, of about 37,000 lb. per sq. in. to about 115,000 lb. per sq. in. as the metal strain-hardened. Then, to show the progressive rising of the yield point as the metal is plastically cold-worked, the second blank was squeezed down step by step. After each additional squeeze the blank was removed from the machine to be measured and tested for hardness, and then returned to the machine without disturbing the recording apparatus. After being squeezed to half its thickness, it was reannealed and the squeezing test continued.

In Fig. 184, showing the original curves for both blanks, note that in contour the curve taken without interruption coincides almost identically with that taken step by step. The latter has been reconstructed in Fig. 185 with irregularities neglected. In the reconstruction, the measurements taken have been used to convert the stress to pounds per square inch, to eliminate the misleading effect of increasing area as the blank diameters were forced to increase.

In Fig. 185 we have in effect a series of separate tests. In each, the pressure rises elastically to a yield point and then follows a plastic curve

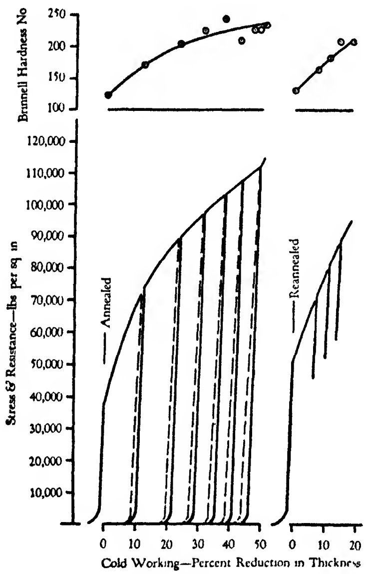


FIG. 185.—The curves at the right in Fig. 184, rearranged to show increasing yield points in unit stress values.

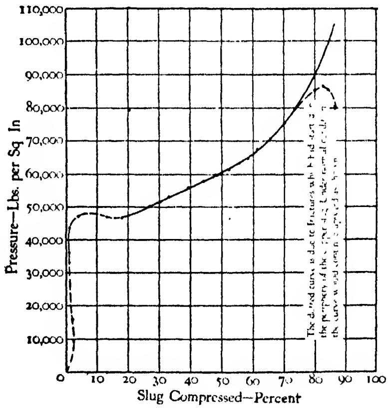


FIG. 186.—Yield point and increasing unit resistance to cold compression of cold-drawn copper slugs.

to the cessation of that test. Placed together, the plastic portions form a continuous curve, a part of the rate of strain-hardening curve. Each yield point indicates the amount of work previously done on the metal, whether it was done by squeezing, stretching, rolling, bending or drawing. The drawn rod, as received and before annealing for the test, showed a yield point in compression over 100,000 lb. per sq. in. It annealed to a yield point of 37,000 lb. per sq. in. Compression raised this yield point to 115,000 lb. per sq. in. Reannealing reduced it to 45,000, and further compression again raised it to 95,000. Neither annealing reduced it to the low value of 23,000 lb. indicated in Fig. 19.

Figs. 186 and 187 show another case in point. A series of slugs were prepared, of identical dimensions, from cold-drawn copper rod. They were then squeezed between flat, hardened and ground surfaces to about two-tenths of their initial height. This was done step by step in Olsen testing machines. Fig. 186 shows a curve plotted from over a hundred readings illustrating the change of resistance as the metal was cold-worked. Certain good authorities give copper an elastic limit between 730 and 29,000 lb. per sq. in. Probably yield point would be a better term. Others suggest 8000 as the value. Yet Fig. 186 shows it quite clearly between 45,000 and 48,000 lb. per sq. in., indicating that the cold-drawing process, by which the rod was produced, had strain-hardened the metal materially. The hardness rose from scleroscope No. 73 to No. 93 during the test. Toward the end all favorably placed slip planes were used up and the curve began to rise

Fig. 187.—Copper slugs squeezed cold to as little as 14 per cent of their original thickness, without annealing.

sharply. Then internal and edge fractures appeared and the curve dropped.

From the foregoing, if a slug or blank is to be subjected to a small and unimpeded movement, its test yield point prior to the squeezing operation will very nearly coincide with the resistance it will offer to the machine doing the work. If the metal is reduced to a fraction of its original thickness the resistance offered will rise materially above the initial yield point. And yield point is not a fixed value for any given metal but varies over a wide range according to thoroughness of anneal and subsequent cold-working.

The cold-work range for a metal is that below its recrystallization temperature, as discussed in Chapter VII. As the working temperature nears that of recrystallization, strain-hardening is less rapid. At or above that temperature, as in zinc, tin and lead at room temperatures, strain-hardening occurs to a limited extent, when the material is worked quickly, but its effects disappear with time.

Fluidity and Restraint of Flow.—A part of the rise in pressure in Fig. 186 is not due to strain hardening but to a rising interference with

the freedom of movement of the metal. It is interesting in this connection to consider the material both as an elastic solid and as a fluid.

In Fig. 188, sketches *a* and *b* are arranged to illustrate the elastic condition. The plan view of a flat disc is divided into rings of equal area. Pressure exceeding the yield point, S, of the material should move metal within, say, the inner ring of diameter d. Yet to squeeze this ring thinner means increasing its diameter, and this in turn means stretching the rings around it. The fluid pressure, P, within this inner ring to stretch the rings of yield point S about it, may be arrived at by formulae which reduce to $P = SD/d$. Applying this to each ring successively we obtain a squeezing pressure building up from the yield point around the outside to many times that value as shown in sketch *b*. This analysis is theoretically not affected by increasing the thickness or height of the slug to the proportions of a column.

If the metal is considered as a fluid mass, on the other hand, the pressure would be the same at any point or in any direction (Pascal's law). That is, it would be impossible to build up higher pressure toward the center.

In practice, however, the extreme "viscosity," or resistance to flow, of the metal, creates a condition midway between these two theoretical cases. As the metal becomes thinner with relation to its area, the squeezing pressure builds up toward the center to values far above the yield point.

Thus the thinnest blank in Fig. 187 resembles 188 *c* and *d* in that it is measurably thicker in the center than at the edges. This is due to relatively greater deflection of the hardened squeezing steels toward the center of the disc, which in turn is due to relatively higher pressure in that area. Yet, as the curve of the surface indicates, the pressure does not rise sharply as in sketch *b* but gradually as in sketch *e*.

Sketch *e* in Fig. 188 shows the fluid pressure found experimentally in thin films of lubricant in loaded bearings. The lubricant naturally tends to escape at ends of the bearing where the flow is unrestricted. Yet because of its viscosity and relative thinness it builds up a high pressure resistance.

Note incidentally that the thin sample in Fig. 187 shows tensile fractures all around its outer edge, indicating the severe stretching of the outer rings of material as the inner rings expand them.

From the foregoing it is clear that the squeezing of thin plates of large area is relatively very severe and capable of building up unduly high local loads on the die steels and press, and such proves to be the case in practice. For the sake of both tools and machine the die surfaces should be relieved wherever possible.

Fig. 189 illustrates a few typical squeezing jobs in cross-section arranged to show methods of relief, and restrictions to flow.

Sketch *a* (Fig. 189) represents a typical sizing operation on a drop forging. The boss is to be bored as indicated by the dotted lines, so that there is no need of flattening the entire face. Accordingly, the forging die is arranged to give the depressions shown, thereby cutting down instead of building up the load on the die steels. The relief might be obtained with depressions in the die instead of the forgings, but this would mean more expensive die steels and accurate location of the forging each time. Most sizing operations are comparatively easy in that

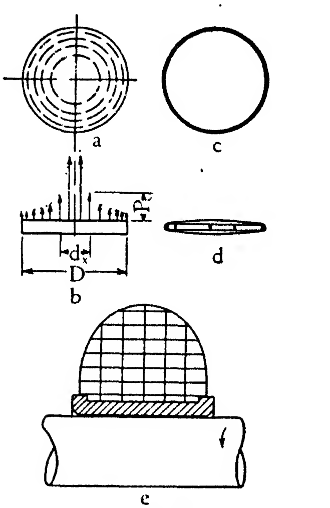


FIG. 188.—Pyramiding of pressure toward the center of a blank and of a thin fluid film.

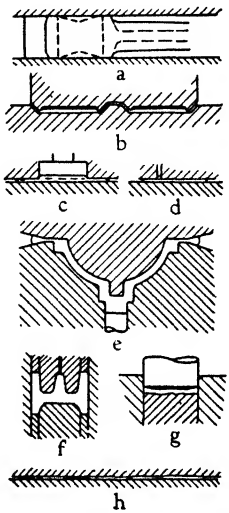


FIG. 189.—Freedom of flow or restriction to flow of metal in typical squeezing operations.

the area being squeezed is small compared with the thickness of the forging, the flow is relatively little and there is rarely any restriction to lateral movement of the metal.

In the case shown, the flow and strain-hardening effect will be pretty well localized at the surfaces, as the horizontal cross-section is the least there. This is desirable both to give a good surface and to avoid changing center distances or structure in the body of the forging. Variations in forging thickness, spring-back and the use of size blocks will come up for discussion later.

Sketch *b* (Fig. 189) shows a push-button wall-plate stamping, the front corners of which must be sharp. It is impossible to get this effect,

no matter how great the pressure, unless the whole face of the punch is relieved so that pressure is exerted only along a narrow line inside the corners. Bending naturally thins the metal at the corner, and actual coining must take place to obtain a fill. Limiting this coining to narrow lines just where it is required prevents a building up of pressure and keeps the load on tools and machine within reasonable limits.

Sketches *c* and *d* (Fig. 189) show typical cold forging or swaging operations where a blank is cut having approximately the thickness of the thickest portion of a desired shape. The balance is then squeezed down to perhaps a half or third of its original thickness and finally is trimmed and possibly shaved to a desired outline. The proportion of the area squeezed to its final thickness determines the severity of the operation. Accordingly, sketch *d* illustrates a much more severe job than sketch *c*, and actually the tools for it require more frequent redressing and the average results are not so accurate. The thin portion of part *c* is to be trimmed into gear teeth (for an adding machine). Accordingly the blank is developed to a gear tooth outline which, after the squeeze, will leave a minimum to be trimmed off. This development helps to keep down the area to be squeezed and eases the tool load.

Sketch *e* (Fig. 189) illustrates a rather severe brass press forging. It is severe because the area being squeezed is relatively large compared with the thin section of the flash, which is the point of escape for the excess metal. The last portion of the punch advance causes a considerable flow of metal from the center out, and the narrow part sets up quite a back resistance. With reasonably careful control of volume and set-up a closed-die forging job such as sketch *f* is really less severe on the tools.

Sketch *g* shows a typical coining job as in mint work. Here again closed-die construction is used and the pressure reduces the thickness of some parts of the blank causing it to thicken and fill in other parts.

Sketch *h* (Fig. 189) represents a large, flat, steel blank squeezed over approximately its entire area, to produce, in this case, an effect of etching. For practical purposes this also may be considered as a closed-die job, for the relation of area and thickness is such as to preclude any relief from flow of the steel without injury to the dies.

Extrusion will be left for consideration by itself. The dies are not entirely closed, of course, but the velocity of flow through the small orifice is responsible for high loads in proportion to the metal yield point.

For convenience, squeezing operations may be divided into four general groups approximately according to their severity. A measure of this increasing severity is found in the fact that the groups are largely

limited to the working of progressively softer and softer metals. There are, of course, some exceptions.

Classification.—The first and ordinarily the least severe is the mere sizing, flattening or surfacing of forgings, stampings or castings in iron, steel or softer metals. Here, there is ordinarily little if any restriction to flow and the amount the metal is moved is relatively small.

Second is swaging, cold forging or upsetting, where a suitable blank or slug is forced into a desired shape to save machining. This usually involves considerable free flow of metal in some portions of the job. Some steels, preferably of low carbon content, and the softer metals can be worked in this manner.

The third division is coining, stamping or embossing, in which the metal, fairly well confined and usually in comparatively thin sections, may be forced to flow to fill the shape and profile of the dies. Coining gets its name from preparation of coins in the soft precious metals and has been extended to the working of brass and the white metal alloys. Stamping and embossing operations are frequently found in the working of steel, but in such cases either the die is carefully relieved to limit the working area to narrow lines, or considerable care must be exercised in making set-ups to avoid overloads.

Hot forging operations should undoubtedly be considered with the third division. The flow is considerable up to the point where the metal fills a closed die or reaches the narrow flash relief of an open die. Some steel and much brass is press forged.

The fourth group is extrusion, in which the metal is forced to flow more or less rapidly through an orifice of the desired shape. The conditions are generally very severe, limiting practice particularly to tin, lead and aluminum, and in certain cases to zinc, brass and copper.

Sizing Drop Forgings.—In the first group, sizing operations, where the metal is usually moved very little and without restriction, the most general application and the one receiving the greatest attention is the sizing of steel drop forgings. Fig. 190 shows a random selection of drop-forged automobile parts on which flats, angles or boss faces have been squeezed to size in knuckle-joint type presses. The object, of course, is to squeeze the boss surfaces of the unfinished forgings accurately to size so that the usual milling or grinding operations are unnecessary.

The trade reports that under favorable conditions one operator and one press can size cold four to eight or ten times as many parts as can be milled or ground by one operator with a suitably rigged machine-tool. And where the quantity is sufficient and the shape of the part is adaptable, a magazine push feed can be applied to the press and the rate increased by another 25 to 50 per cent.

The division of the General Motors Corporation which furnished the samples shown in Fig. 190 advised that their usual tolerance for such work was plus or minus 0.001 in. This is fairly representative and is closer than tolerances ordinarily used on the milling of such parts.

A division of the Chrysler Corporation reports that they rough-size their connecting rods to about +0.010 in. and then finish-size them to a close tolerance in a 1000-ton knuckle-joint press.

The dies for sizing bosses are usually plain blocks with comparatively large surface area so that the forging need not be located with especial care. For close limits, size blocks or contact surfaces are built

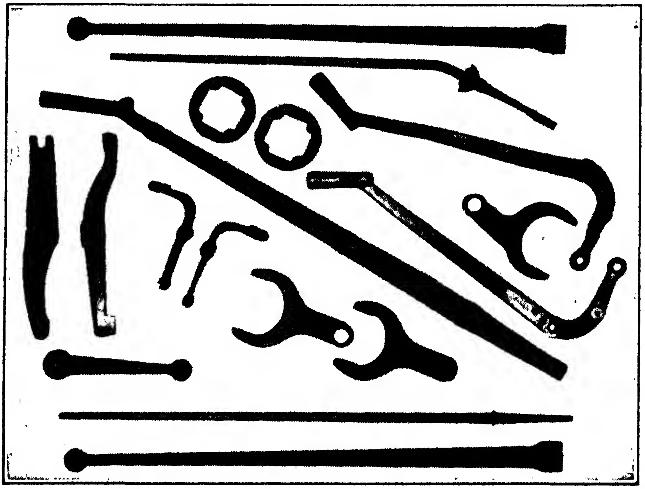


FIG. 190.—A group of automotive drop forgings including also two malleable castings, on all of which bosses or other surfaces are coined to size, displacing machining or grinding operations.

into the dies. These may take the form of parallels between the punch and die. The object of this construction is to insure having the squeezing surfaces of the dies come to the same place each time. Without it, variations in the original thickness of the forging and in its hardness result in a varying load on the press and consequent variations in the several oil-film thicknesses and in die and bolster deflections. Practice varies regarding the area of contact surfaces, but using hardened surfaces with twice the area of the surface being sized has given excellent results. In this case, about two-thirds of the pressure may be exerted upon the contact blocks, and the press must be selected on the basis of three times the working pressure plus the usual margins.

The error or variation which cannot be eliminated is that due to differences in elastic spring-back. Fig. 191 shows the curve recorded in a compression test of a ¾-in. diameter disc of commercial cold-drawn steel rod ¼ in. high. The test was performed in an Olsen recording testing machine and carried to a 20 per cent reduction, showing an initial yield point at about 50 tons per square inch, the stress rising to about 63 tons per square inch at the end of the desired squeeze. The recorded plastic flow from the yield point to the end of the curve (about 0.042 in.) agrees reasonably with the permanent set shown by the dimen-

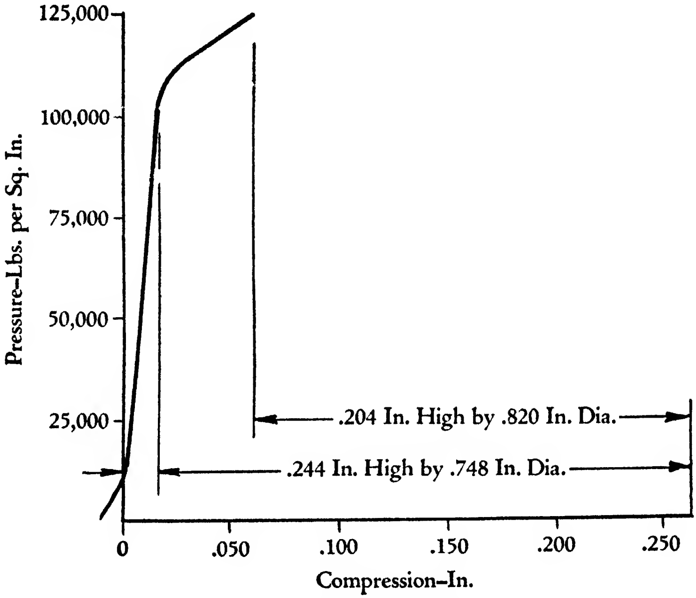


FIG. 191.—A compression test of ¾-in. diameter commercial cold-drawn steel showing elastic deflection and plastic strain-hardening.

sions of the slug (0.244 − 0.204 = 0.040 in.), and indicates that the spring-back must have about equaled the recorded elastic deflection (approximately 0.018 in.). Half of this seems to be in the tools, but 0.009-in. elastic spring-back or about 4 per cent of its length appeared to be in the piece. This compares with a 0.0007-in. theoretical elastic deflection.

Table XIX gives test results covering the apparent elastic spring-back of cast-iron piston rings after sizing, and illustrates the variations resulting from structural differences in the material. In this test, rings which had been faced off were squeezed between substantial hardened-steel die blocks separated by hardened distance pieces 0.1173 in. thick.

Table XIX

SIZING THICKNESS OF CAST-IRON PISTON RINGS[a]

Thickness, inches	At Gate	At Riser		
Changes, inches	0°	90°	180°	270°
Specimen 3	Squeezed in 400-ton knuckle-joint press			
Before squeeze	0.1226	0.1228	0.1227	0.1223
After squeeze	0.1198	0.1200	0.1198	0.1196
Permanent set	0.0028	0.0028	0.0029	0.0027
Spring-back	0.0025	0.0027	0.0025	0.0023
Specimen 4	Squeezed in 400-ton knuckle-joint press			
Before squeeze	0.1221	0.1223	0.1223	0.1226
After squeeze	0.1191	0.1200	0.1200	0.1196
Permanent set	0.0030	0.0023	0.0023	0.0030
Spring-back	0.0018	0.0027	0.0027	0.0023
Specimen 6	Squeezed at 400 tons in hydraulic press			
Before squeeze	0.1228	0.1228	0.1223	0.1224
After squeeze	0.1215	0.1217	0.1213	0.1216
Permanent set	0.0013	0.0011	0.0010	0.0008
Spring-back	0.0042	0.0044	0.0040	0.0043
Specimen 9	Squeezed at 600 tons in hydraulic press			
Before squeeze	0.1233	0.1230	0.1230	0.1233
After squeeze	0.1204	0.1213	0.1209	0.1211
Permanent set	0.0029	0.0017	0.0021	0.0022
Spring-back	0.0031	0.0040	0.0036	0.0038

[a] Tools all hardened and ground tool steel: 0.1173-in. spacers between ¾-in. blocks backed by 2-in. thick blocks. Test by W. P. Blake and A. E. Caserta.

The elastic spring-back from this figure varied between 1 and 5 per cent of the ring thickness (0.0017 to 0.0052 in.). The variation in thickness in any individual ring after sizing varied from 0.0005 to 0.0010 in. Cast iron is notably not uniform in density on account of air holes, voids, inclusions and non-uniform crystallization. The cast piston rings developed a noticeable softness, near the point where the gate had been attached, amounting to a five-point difference on the scleroscope (40-45). This relative softness resulted in general in less spring-back and greater permanent set.

Returning to drop forgings, the usual *finish allowance* for sizing is about 1⁄32 in., although in some cases it is as much as 1⁄16 in. More can be allowed but is not required and may prove troublesome. If the rough forgings vary considerably in thickness, the pressure which the press is called upon to exert will vary also, as indicated, for example, by Fig. 191.

The forging to be sized may, of course, have a number of different finished surfaces at varying levels, which are taken care of by corresponding steps in the die. The relative heights of such bosses on the sized forgings are found more reliable than they would be if the piece had been machined. Sizing of forgings is not limited to the flat surfaces of bosses. Rounds, bevels, sides, tapers, flanges, even the inner surfaces of punched holes, can be sized smooth and accurate. One thing to watch, especially in sizing steel, is to have ample space for the free flow of the metal in order not to restrict it so that the pressure builds up. A certain amount of restriction is possible, but it necessitates greater care in construction of the die, and the life of the tools is proportionately reduced.

Referring to Fig. 189 *a*, attention was called to the fact that forging a depression in the center of bosses prevents pyramiding of pressure there, which is hard on dies in a squeeze of large area, and localizes the deformation at the surface of the boss. Such forged depressions are also illustrated in the boss on the gear-shift lever in Fig. 190. If the upper face of a boss is larger in area than its lower face, the metal movement and therefore the smoothing and squaring-up effect will be localized at the small end. Working naturally occurs where the resistance to metal movement is least. Considerable local surface movement may be expected to give a smooth surface and some surface strain-hardening.

To compute the load requirements in the free-flow sizing of drop forgings A. R. Kelso reports compression tests made in Olsen testing machines. A 0.45 C steel (S.A.E. 1045), having a Brinell hardness of 197, showed a yield point of about 82 tons per square inch. A 0.25 C

steel (S.A.E. 1025), having a Brinell hardness of 137, showed a yield point of about 50 tons per square inch. The actual load will be greater than these figures indicate, by a small or a large margin, depending upon the freedom of flow and the increase in resistance due to strain-hardening (Fig. 191). Allowance must be made for the equalizing pressure to be applied on the size blocks if these are used. Beyond this, most press manufacturers recommend an allowance of about 100 per cent owing to the positive action of the press and the possibility of oversetting or feeding oversize blanks on work of this sort. Several automobile manufacturers select their sizing presses on a basis of 100 to 200 tons per square inch of forging area to be squeezed.

Warmth in Sizing Operations.—Some shapes may present too large a surface area and therefore require too great a pressure to admit of cold sizing in available press equipment. Or the shape may be too intricate or too thin in proportion to its surface area for successful cold sizing. In either case, some advantage may result from a warm or hot squeezing operation below the temperature at which the metal would oxidize and form scale. The use of such an operation may reduce the required machining to merely a finishing cut or may possibly eliminate it if tolerances and surface finish are not particular. The accuracy of cold coining cannot be expected from such operations, as any variation in temperature will result in a difference in the amount the metal yields under pressure and in the amount it shrinks in subsequently cooling to room temperature. It has been suggested that the parts be sized immediately after forging or after annealing in order to avoid heating charges. In either case, non-uniformity in sizing temperature and the formation of scale would have to be avoided.

Sizing and Surfacing Castings.—Castings as well as forgings are frequently squeezed to dimension. Many brass, bronze, aluminum and alloy castings and some steel and malleable castings lend themselves to cold sizing and surfacing methods. Two L-shaped malleable cast-iron brake levers in Fig. 190 come in this class. In such cases the same general comments apply as have been made on the sizing of drop forgings, except that the yield points of the softer metals are materially lower with proportionately lower press requirements. In the use of brass there is an increasing tendency to resort to hot press forgings for many shapes, the accuracy being very nearly as close as could be obtained by cold sizing a drop forging.

Another application of squeezing methods to castings is found in the preparation of some classes of hardware for plating. The surface of the casting can be coined sufficiently smooth to eliminate or greatly reduce the preparatory hand work and buffing. In Fig. 192 is shown a cast

handle which is surfaced in this manner for nickel plating, a fin of surplus metal being forced out which must be shaved off later. The pressure allowance for this job should be about 90 tons per square inch of projected area.

The finish obtained in sizing and surfacing operations depends upon both the part and the tools. For a high finish on cold-rolled steel strip or sheets the mill rolls must be ground and polished to a high degree and the strip must be absolutely clean and reasonably smooth before the finishing pass. With equal care, a similar finish may be obtained in

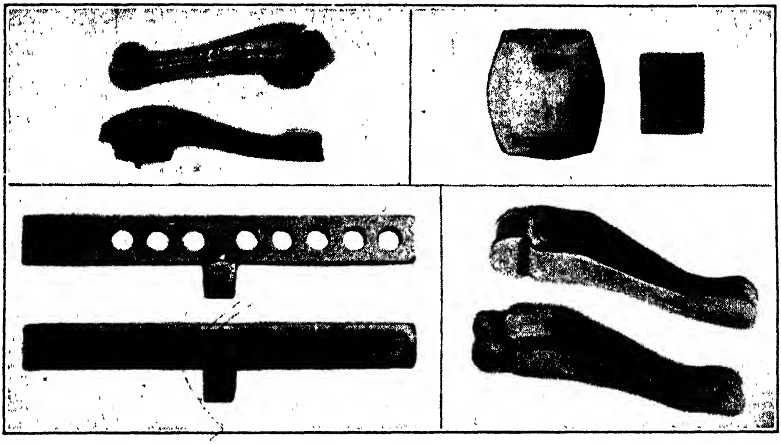


FIG. 192.—(*Upper left*). A cast-brass handle of an automobile door squeezed in a knuckle-joint press to prepare its surface for plating.
FIG. 193.—(*Upper right*). A mild steel blank squeezed down to leave an extending lug of the original metal thickness.
FIG. 194.—(*Lower left*). A severe sizing operation to square up top, sides and hole walls of a steel blank.
FIG. 195.—(*Lower right*). A sizing operation to square up the edges, corners and bottom of a formed lever.

sizing operations. It may be expected, however, that any tool mark or scratch on the surface of dies will leave its impression on the surface of the work, and shallow gouges or scratches on the work may necessitate considerable surface movement or squeeze to smooth them out. It is easy to pick out on a blank, stamping or forging the very smooth areas where sufficient pressure has been exerted to cause surface movement. Scale and the thinner oxides break up with the surface movement and spread, if the movement is sufficient, leaving patches of clean metal. It is often possible to follow the metal movement by the movement of the oxide on the surface of a severely worked piece. Thus in Fig. 193

the outline of the blank is clearly visible on the surface of the swaged sample. If necessary, a mirror-like finish can be obtained by squeezing smooth and absolutely clean metal between highly polished dies.

Sizing Stampings.—Many sizing operations are required on parts stamped out of rolled metal to square up, set down, flatten or otherwise correct surfaces or the relations between surfaces. Thus in drawn shells it may be a squeeze to insure proper relation between locating flanges at the top and the bottom.

Fig. 194 shows a bar blanked out of steel about 0.156 in. thick. The metal was fairly soft, as indicated by the rounded corners. It is then pierced and squeezed in a closed die to square up and fill out not only the top and bottom but the fractured surfaces of the sides and holes. Being a closed-die operation, and moreover performed on steel, it is extremely severe—much more so than most sizing work. The press should really be selected on a basis of 200 or 250 tons per square inch. And if it is a very rigid type the metal thickness should be watched carefully.

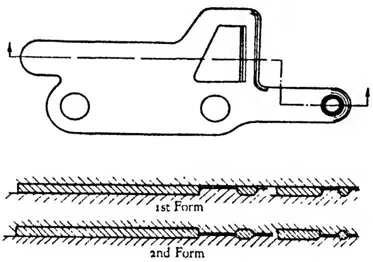


FIG. 196.—A heavy-gauge blank the edges of which were radiused in two operations.

Fig. 195 shows a lever as formed up (shown above). It is then placed in another die and restruck or sized to give square true edges, sharp inside corners, thicker walls and a flat bottom. The appearance of the stamping is thereby very much improved, and it is held to closer tolerances than is possible in merely forming.

Fig. 196 illustrates a sizing operation the function of which was to radius the edges after blanking. The part was blanked out of ¼-in. hot-rolled steel and pierced afterward. It will be noted that the squeezing operation is unbalanced, and there would be a tendency to move the blank to the left. To overcome this it proved necessary to do the radius forming in two operations, using a flat punch for the first, as illustrated. Under more favorable circumstances a single operation may suffice.

The mere flattening of washers, discs or other blanks in sheet metal is a simple operation fraught with possibilities of trouble. As a rule, all that is required is a light blow to take out some obvious buckle and flatten burrs. It is a large jump from the pressure required to do this to a pressure sufficiently great to exceed the yield point over the entire surface of the blank and give it permanent set. Yet the difference in press adjustment is small, only enough to compensate for increased deflections. Presses selected for flattening in a practical sense, but not

for coining, are therefore subject to possible breakage with careless handling. The hydro-pneumatic overload relief mechanism in the press-bed, Fig. 246, and the high-speed hydraulic press, page 213, are of especial value in such cases.

Cold Forging.—The second group of cold-squeezing operations occupies a large range between the relatively low stresses involved in most sizing operations and the relatively high stresses in coining.

Fig. 197 shows a group of rough parts squeezed to large limits in hot-rolled steel with no restriction to flow. The piece at the bottom becomes two wedges after the first squeeze which forms the taper. A subsequent sharper-edged squeeze will all but complete the edges and sever them. Above in the center is a link made of round rod formed with the two ends overlapping. The two ends are then squeezed together cold, making a strong job without welding. The cross-sectional area of that portion

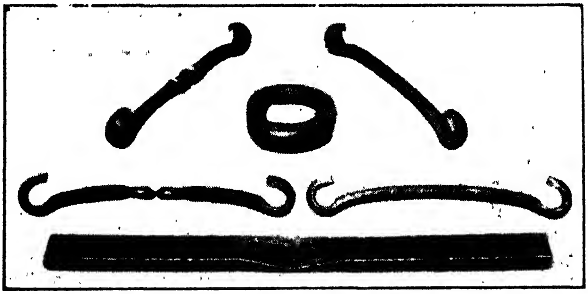


FIG. 197.—Parts cold forged out of hot-rolled steel.

of the link is practically double that of the rest of the rod, but this is not objectionable for the service involved. The other links shown are also made from round rod. The space for the ends, two ends together, is flattened; adjacent links are parted in a second die, then formed and finally returned to the knuckle-joint press to coin the two eyelets at the center.

Fig. 198 shows a small knuckle-joint coining press of 50 tons' rating in use on a free-flow squeezing operation. The operator, with a handful of small steel rods, is flattening one end of each rod into a good-sized boss for an eye. Some of the product is shown in the box at the right. In this operation, which is a rather common one, the metal is usually permitted to take its natural outline without constriction as the operation is fairly severe even without such a handicap.

Fig. 199 includes sections of three bars representing three cold-forging operations on copper in the production of a contact point. In the first operation a series of notches are squeezed into the 10-ft. bar, one

notch per stroke; next the pockets or depressions between notches are squeezed in, also one per stroke. Next rivets are dropped into the depressions by hand, and another squeezing operation closes in the metal around them and finishes the shape of each piece. A final trimming and parting operation completes the job.

Copper is quite a popular metal to cold-forge. It strain-hardens slowly and can be worked to a very considerable extent. Hardness which can be obtained in this manner is often a desirable feature. On the other hand, hot forging copper is usually troublesome on account of the hard black oxide which forms and erodes the dies. Furthermore, hot-working operations are always relatively expensive and difficult to keep up. A small percentage of lead is sometimes alloyed with copper for the extrusion of long stems and other very severe operations.

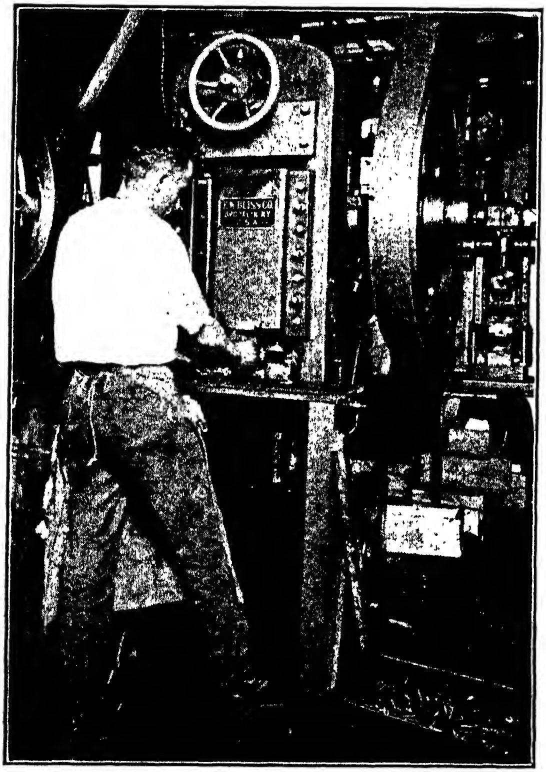


Fig. 198.—A 50-ton knuckle-joint press used in flattening the ends of rods into bosses.

Rivet forming or extrusion, Figs. 200 and 201, again involves a wide range of pressures. The term extrusion seems properly applied in quite a few cases, although true extrusion which comes later is relatively much more severe. The same letters are used to designate parts in the photograph and their corresponding cross-sections in the line drawing.

At *a*, *d* and *f*, a flat extruding punch is used which is larger in diameter than the rivet shank or dowel lug that it is to produce. This sets up a free flow into the lug and a restricted flow out to the body of the blank. Most of the metal displaced goes into the lug, making it fairly high. At *c* an even higher lug is obtained by stepping the extruding

punch to a diameter which is smaller than that of the lug as well as the principal diameter which is larger, thus displacing even more metal.

The job illustrated at *d* is similar to that at *a* except that the lug or shank is extruded out of the softer steel right through holes previously punched in the thin spring steel member, and is turned over or riveted all in one stroke, completing the assembly. The equipment in which this is done is shown in Fig. 202. It includes a standard inclinable press and dial feed. The latter is fitted with a series of assembly posts provided with means of locating the steel vibrator spring and the softer bridge piece. The operator is able to feed about sixty assemblies a minute, which are picked off automatically as completed.

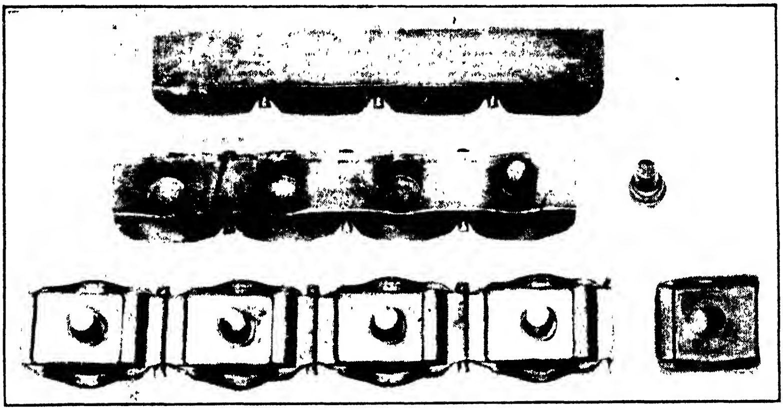


FIG. 199.—A series of cold-forging operations to produce a copper contact point.

Returning to Figs. 200 and 201, parts *e*, *g* and *h* represent a more severe method of forming rivet lugs in which the thickness of the entire blank is reduced in order to leave the lug protruding. That shown at *e* is the most severe, owing to the thinness of the part compared with its area. It may be anticipated that the finished blank will be several thousandths of an inch thicker in the center than at the edges because of pyramiding of pressure and consequent deflection of the die steels.

The garden trowel handles at *g* are formed complete, two per stroke, in a single operation. This includes bending the (round) rod, squeezing the ends to produce the blade rivets, squeezing the handle stops and pinching the two apart in the center. With a mechanical feed it would not be difficult to make the whole job automatic.

At *h* is shown a pen-knife bolster cold-forged progressively from round rod and later trimmed out of the flash as indicated in the photograph. At *b*, *j*, *k* and *l* are shown cold-squeezing operations apart from

the forming of rivet shanks but sufficiently related to be included here.

A deep chamfer or countersink as illustrated at *b* is quite a severe

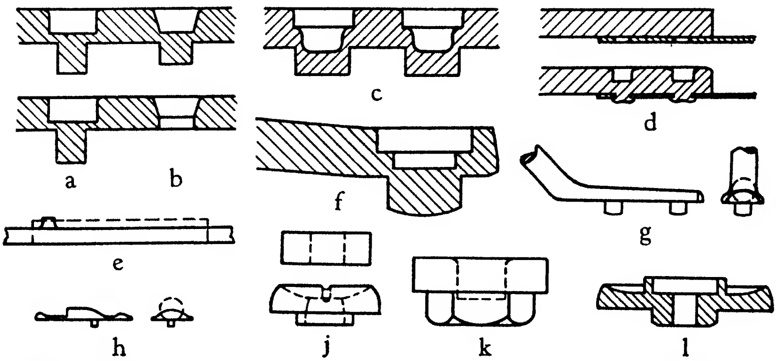


FIG. 200.—Cross-sections to scale, of parts shown in Fig. 201, showing metal displacement to form rivet lugs.

job when produced in the normal manner of piercing the hole first and then attempting to squeeze the surplus metal out into the solid surround-

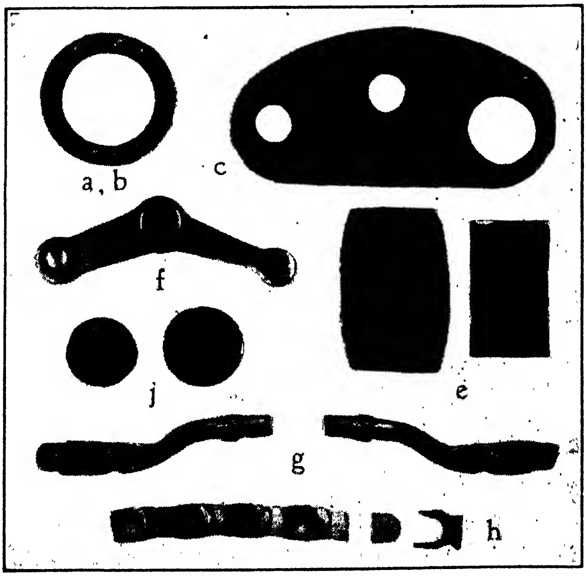


FIG. 201.—The cold forging or "extrusion" of rivet lugs and similar operations.

ing blank. Remember always that metal displaced must go somewhere. Accordingly, in the method shown, the surplus is pushed through the

blank, ahead of the countersinking punch, with large clearance. The piercing operation then follows to finish the job.

At *j* (200–1) is shown a bronze ball seat bearing and the blank from which it is forged (cold). The relative diameters of the slug and hole are such as to allow a little flow both in and out. A pilot enters the hole to prevent its closing in too much. The offset and the oil groove are squeezed in. Oil grooves in bushings formed up from flat strip are coined before the forming operations, in a similar manner. The bronze used for the job shown contains about 5 per cent tin, 1 per cent lead and the balance copper.

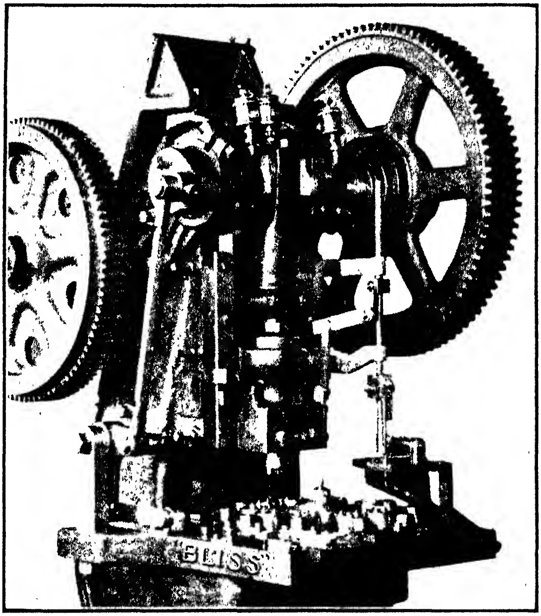


Fig. 202.—The press and feed used to assemble the vibrator spring and bridge piece, Fig. 200*d*, extruding and riveting complete.

Sketch *k* indicates a method of cold-forging copper nuts for electrical work in a method similar to *j*. The blank is a plain cylindrical slug sawed or sheared from round bar stock.

Sketch *l* is a cross-section of a rectangular steel nut formed by a combination of extruding or offsetting in the center and coining around the outside. The original thickness of the metal has been decreased relatively little by dragging down adjacent areas.

Owing to reasonably close control of dimensions afforded by the tools, the rivets formed as shown in Figs. 200 and 201 are usually set down or riveted over satisfactorily in a regular power press. For setting down ordinary commercial rivets in pierced holes, however, the variations in dimension may be such as to make a constant-pressure equipment desirable. Figs. 203 and 204 show typical arrangements combining the speed and convenience of mechanical operation with the constant-pressure feature. In the former, a press built for riveting operations is equipped with a built-in hydro-pneumatic cushion to

prevent any load in excess of the desired maximum. Similar hydro-pneumatic pressure-control cylinders are built into the beds of both the knuckle-joint coining presses and the eccentric shaft forging presses to compensate for variations in blank thickness or for cold blanks (in hot forging), etc.

In Fig. 204, a regular horning press, used for a riveting operation, is equipped with an air cushion for maintenance of a uniform riveting pressure through the mechanical advantage of the lever shown. Although presses of this sort are also used in the upright position for such work, the horizontal arrangement has considerable advantage in the handling of a number of the operations on automobile frames.

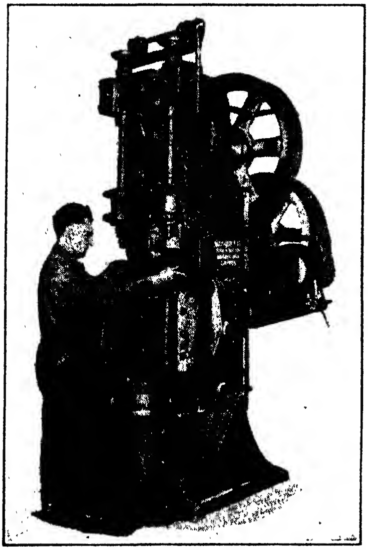


Fig. 203.—A riveting press, with built-in hydro-pneumatic pressure equalizing equipment. (*Courtesy Marquette Tool & Mfg. Co.*)

The upsetting of the flanges of brass cartridge cases, Fig. 205, operations 11 and 12, is in line with other riveting and upsetting operations. Preliminary coining operations on the indentation are performed in steps 3 and 5. The ironing of the side-walls in steps 4, 6, 7, 8, 9 and 10 has much in common with other cold-squeezing operations, although the ironing process was discussed with drawing in Chapter VIII. Upsetting the head required an 800-ton dial feed knuckle-joint press. Hydraulic presses, Fig. 206, are used for the larger sizes. Electrically controlled upper dials permit use of successive indenting, spreading and heading operations.

Swaging.—Swaging should possibly not be distinguished from the previous cold-forging operations, as it has much in common with them.

Fig. 207 shows a typical swaging operation together with preparatory and finishing steps. The part is a counter gear for an adding machine. The blank is produced in a follow-die from material as thick as the thickest portion of the finished part. Its outline is so developed that swaging need take place over an area only slightly in excess of that actually required. The swaging or cold-forging operation itself squeezes down the outer portion of the part and also a step around the hole. This is done in the press shown in Fig. 208. Next the outline

of the gear is trimmed, and finally a shaving operation squares up the trimmed edges of the teeth. Both the first and second operations may be handled automatically. The earlier form of this piece required two parts riveted together and held centrally by a hub on one of them. In the swaging an exact relation between the gear and the single tooth is assured.

Fig. 209 shows a rather interesting collection of sewing machine, business machine and other miscellaneous parts indicating some of the

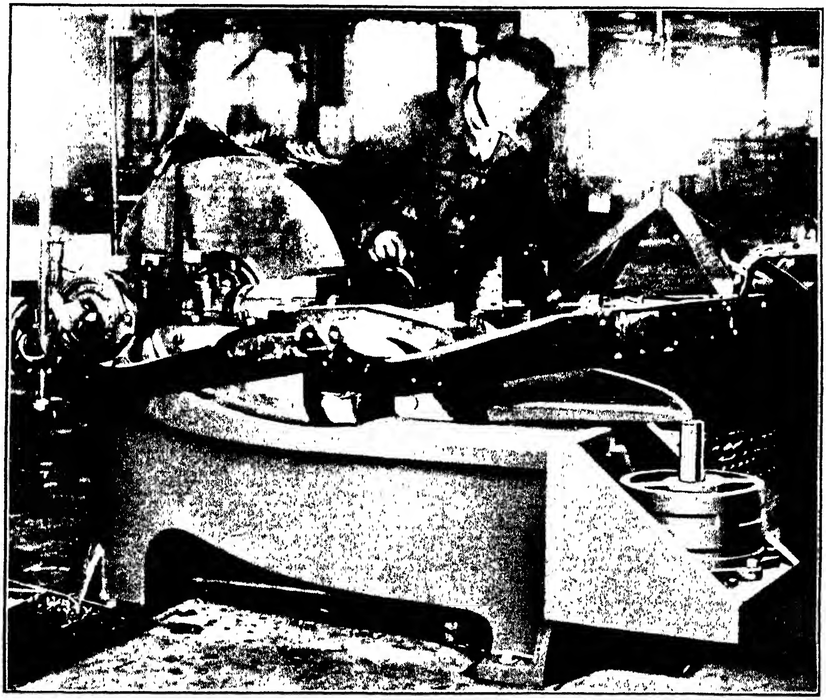


Fig. 204.—A power press equipped with (Marquette) pneumatic pressure equalizer, riveting automobile frames.

possibilities of the swaging method. Series *a* at the top shows a lever pierced and blanked out of steel about 0.125 in. thick. In the second operation a vertical squeeze rounds the edges of the finger grip portion. In the next squeeze the lever is turned up sidewise, and the finger grip portion is flattened and curved to its final shape. The third squeeze indents a cam groove into the large upper part of the lever. A final operation, not shown, is to shave around the sheared edge of the upper portion for finish. This lever, ready for plating in five quick press

operations, is decidedly more economical than a hot press forging requiring trimming, milling, drilling and hand finishing to bring it to the same state.

Series *b* shows first the blank, the swaged piece leaving a hub and four curved pawl fingers protruding and finally the trimming operation to cut out the four blades.

Series *c* (Fig. 209) starts with a blank pierced for an internal spline. The first squeeze carries the metal thickness about the flange down to approximately 50 per cent of its original thickness, and leaves a hub in the center of practically the full thickness. The next squeeze decreases

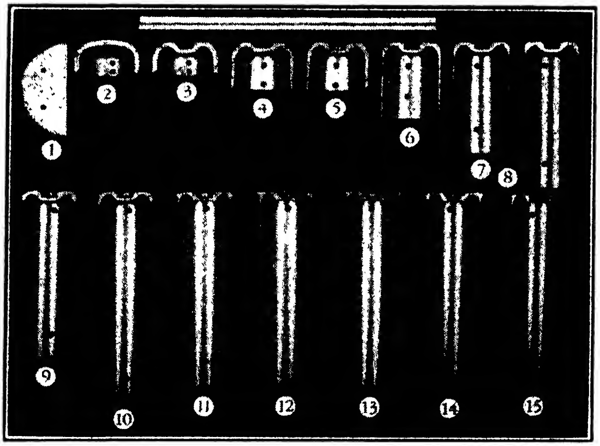


Fig. 205.—In producing cartridge cases, the center indenting and flange upsetting operations (also the wall ironing) are essentially cold forging.

the thickness of the outer part of the flange still farther, leaving a second hub with a single gear tooth protruding. This is followed by a final trim to cut the gear teeth around the outer flange.

Fig. 209 *d* shows a steel plate in the production of which a swaging operation displaces milling to obtain countersunk flanges along the side of each of the three slots. The steps are pre-notching, swaging and trimming the notches. These operations could be performed progressively, shearing off the piece upon completion. To avoid twisting the strip slightly at the notching and possibly at the squeezing station it might prove advisable to use double-width strip producing two pieces at a time, or employ some other arrangement to balance the operation.

Fig. 209 *e* illustrates the production of a flanged square nut. The operations are: pierce and blank, swage, trim.

Series *f* shows three steps in the completion of a small link with bosses at each end. The bosses help to hold the metal against appreciable lengthwise flow. When a blank with a sheared edge is squeezed down to perhaps half its original thickness in an open die, the natural irregularities of the fractured edge surfaces are much accentuated. Trimming of course removes this, and subsequent or attendant shaving

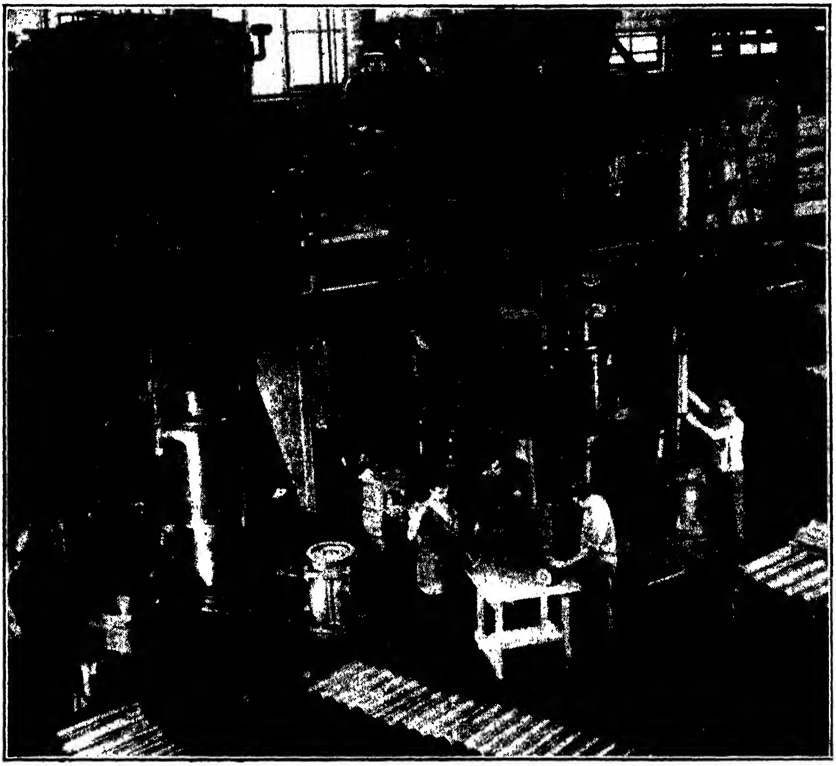


Fig. 206.—Cartridge case heading in 3000-ton high-speed hydraulic presses with three-station lower dial for feeding, heading and unloading, and upper dial permitting use of one to four indenting and heading punches. All functions are electrically interlocked.

gives a very smooth job. The softer metals may be coined complete from a developed blank, the edges being squared up at the same time by the use of a closed die. This has also been done in the case of steel, as in Fig. 194, but that makes quite a severe operation.

Fig. 209 *g* shows a wheel swaged out of a washer-shaped blank of a lead alloy. Series *h* is again steel and shows a cam produced on the side

of a knurled wheel. The series shows the pierced blank, the cold

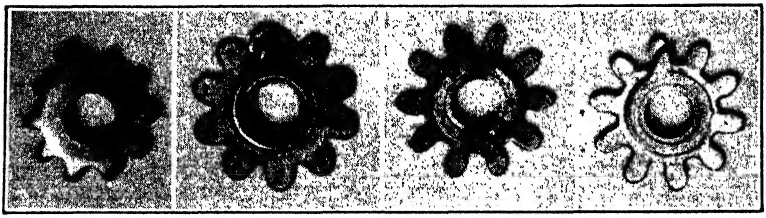


Fig. 207.—A typical counter gear; pierced and blanked, cold-swaged to shape, trimmed, shaved.

forging, the trimmed part and finally the finished part after a deep knurl has been shaved around the edge.

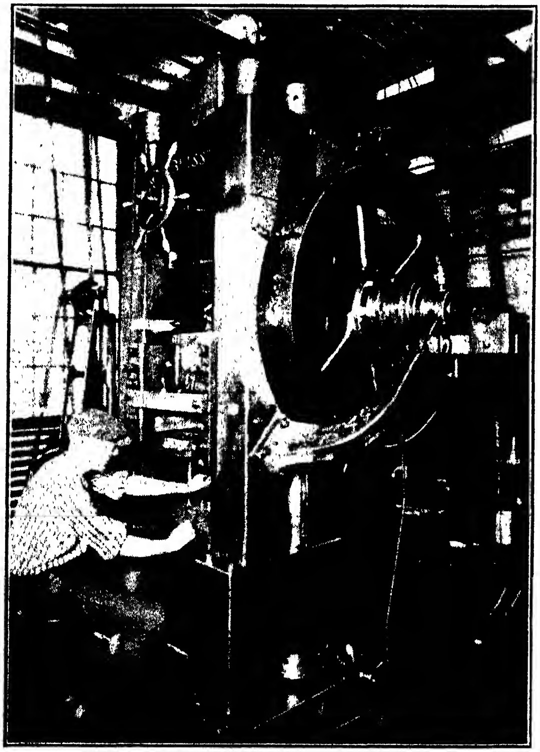


Fig. 208.—A 250-ton knuckle-joint press used to produce the part shown in Fig. 207 and similar work.

Fig. 209j illustrates a series of operations including blanking, swaging, trimming, piercing, countersinking the hole and bending the arm of a small sewing-machine lever. It will be noted that, on all the samples shown of this class of work, the blank is so designed that as little metal has to be squeezed down as is absolutely necessary for trimming or shaving out the finished piece. Note also that in the pieces which have a boss, hub or other portion higher than the rest of the piece, and left so by squeezing down the metal around it, there is a tendency for the corners and edges of such high parts to be dragged down. To minimize this tendency it is

often advisable to use a medium-hard stock (though usually fairly low carbon in steel), and if necessary, to arrange the dies to strike the high

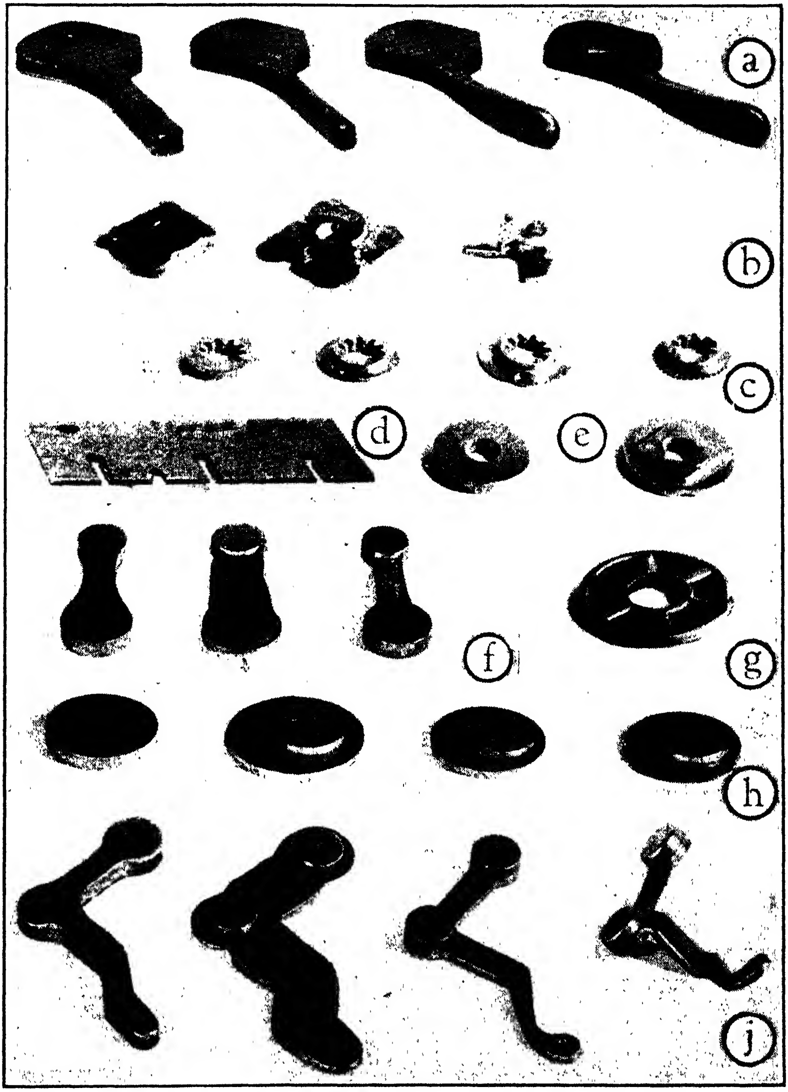


FIG. 209.—A group of parts in which cold-swaging of a suitable blank furnishes the means of economical production.

part at the end of the stroke to size it off a little. Considerable pressure may be required for this work on account of the area and thickness rela-

tion. For practical cases, however, with a free-flow relief all around, it is well to figure, for steel, 100 tons per square inch and higher on the total final area squeezed, and for copper around 75 tons per square inch.

Under the third classification in the squeezing group of operations, including coining, stamping and embossing, comes a variety of work in which the metal is required to flow comparatively little but is subjected to extremely high pressures to bring out sharp designs or lines or to obtain a very accurate surface. On most of this work the metal is either completely contained in a closed die, or practically so, with the result that there is no outlet or relief for the flow of surplus metal. Under such conditions, if care is lacking so that oversized stock is used or adjustments are carelessly made, the rigidity of the presses may

Greece 500 B.C. Egypt 300 B.C. Corinth 300 B.C. Rome 27 B.C.

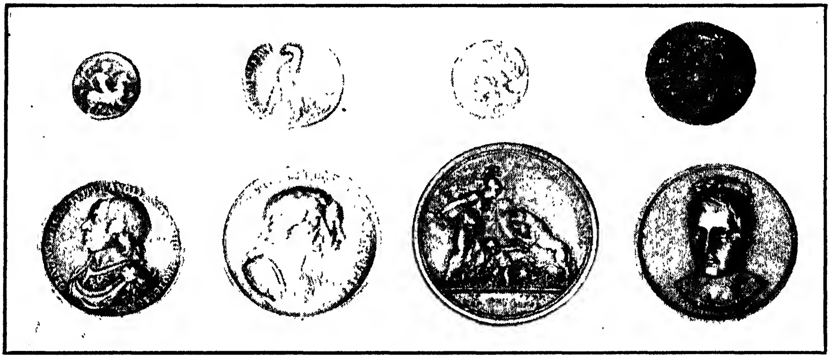


FIG. 210.—*Upper row*: Four ancient coins contribute to the story of early craftsmanship and mechanical progress. *Lower row*: Four excellent examples of commemorative medals from the seventeenth and eighteenth centuries. (*Courtesy of Dr. Frederic R. Sanborn*)

build the pressure up to several hundred tons per square inch with serious consequences to the equipment.

Coins.—In the upper row of Fig. 210 are shown four ancient coins from the collection of Dr. Frederic R. Sanborn. These were " struck " two thousand years and more ago. In many cases the designs are excellent and the tools were well made. The rough outline, however, reflects the crudeness of the methods employed. The lower die was secured on an anvil. A pellet of precious metal was placed upon it. The upper die, hinged to it or held over it by one man, was struck with a sledge by another man. The results obtained would seem to confirm this story. Coins became thinner as time went by, but the irregular outline remained until about the seventeenth century.

The lower row (Fig. 210) shows an interesting group of commemora-

tive medals, the Cromwell medal, 1655, and the Charles II medal, 1670, both struck in England; the American Liberty medal, 1783, and the Napoleonic Egyptian Campaign medal, 1798, both struck at the French Mint. These all have the thorough finish and fine detail of modern coins but were undoubtedly made in crude presses, for the first knuckle-joint coining press, Fig. 211, was not invented, to our knowledge, until 1833. It was brought out by a Frenchman, M. Thonnelier. One of these machines was included in the original installation of equipment for the United States Mint in 1836.

The mint at Philadelphia still has in its possession a simple hand-operated screw press antedating this installation and said to be the

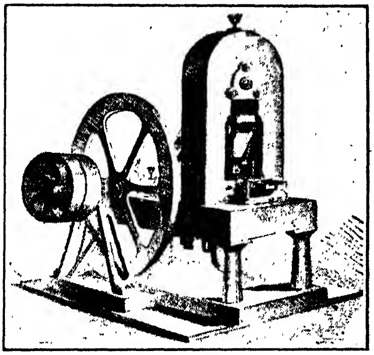


Fig. 211.—The original knuckle-joint press invented in 1833 for the French Mint.

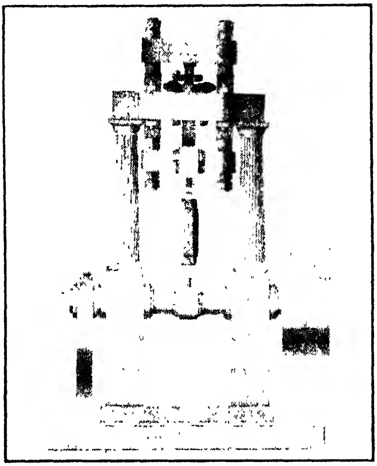


Fig. 212.—One of the early power blanking presses developed for cutting coin blanks.

original machine used at the time coins were first made in this country. It is a small machine mounted on a massive wooden table and was called upon to do both the blanking and coining operations. With power equipment came the Grecian-columned Planchett Cutting Press shown in Fig. 212. It was superseded later in the last century by small, solid-frame, straight-sided presses of the more modern over-drive type.

An even more recent change has been the addition of the Planchett Upsetting Machine, Fig. 213. This machine automatically rolls the coin around edgewise, upsetting and thickening the edge to reduce a certain amount of the strain on the coining dies.

The coining operation itself is now performed in knuckle-joint

presses of the type illustrated in Fig. 214. The coin feed is a development of that on M. Thonnelier's machine and is probably the earliest type of mechanical feed. As now constructed, it includes the tube filled with blanks and a pair of fingers to take the blanks to the die and the finished coins out of the die. A crank-actuated bottom knockout is timed to lift the coin to the surface of the die as the fingers close.

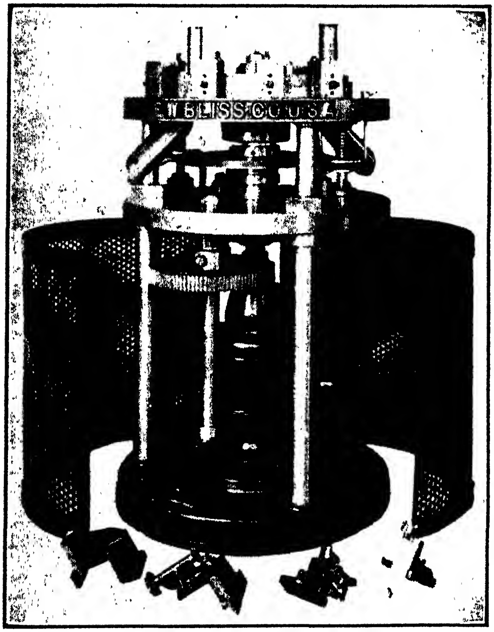


FIG. 213.—A Planchett upsetting machine for rolling thicker the circumference of the coin.

A report issued some time ago by the Mint, Table XX, showed that the actual pressures required to bring up clear impressions on United States gold, silver and copper coins varied between 85 and 125 tons per square inch. These figures are considerably above the freeflow yield points of the metals as rolled, *yet the presses actually used have rated capacities two or three times what the experimental figures would indicate.* This is good conservative practice, for in using closed dies a double blank or a careless set-up will raise the pressure tremendously in a rigid machine. And an extra-rigid machine contributes a great deal to the tool life.

Commercial Coining Operations.—Identical in principle with the production of government coinage are many commercial coining operations. The softer metals in closed dies are forced to flow thinner in some spots in order to fill other thicker spots. There need be no definite relation between the thick and thin areas other than that they be fairly uniformly distributed to avoid considerable offside flow with its resultant side thrust on the punch. In general, the blank thickness is appreciable compared with its area, so that conditions of flow are not too severe.

Trolley tokens and lucky pieces differ little if any from government coinage in production problems. The key blank in Fig. 215 and the nickel-silver flatware blanks in Fig. 217 also involve the same methods, though in the latter case the presses are necessarily larger.

The suspender link in Fig. 215 is typical of certain buckles and other parts which are coined in the stock, then pierced and finally blanked automatically from strip stock. For this work, presses of the high-production type with full eccentric shafts, shrunk tie-rod construction and massive frames are used on account of their greater speed. Ton for ton, they are more expensive than the knuckle-joint type, but they are also more versatile and more compact in their moving parts.

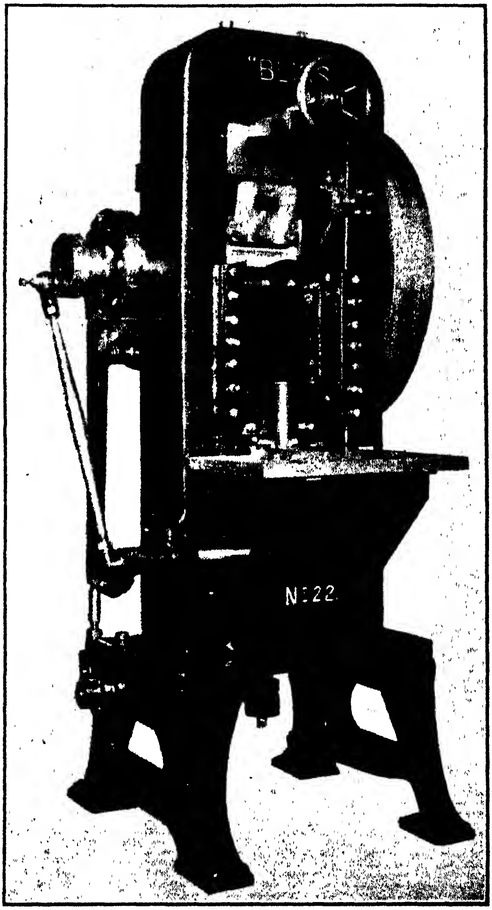


Fig. 214.—The 150-ton coining press of recent mint equipments, equipped with automatic coin feed and cam knockout.

On such progressive operations involving coining it is occasionally found that appreciable non-uniformity in thickness across the width of the stock will cause a greater spreading on the thick side, putting a twist in the stock. If this bothers the piloting or guiding, the clearance may be increased, the arrangement changed to cut the number of pilots or one die may be mounted on a sort of ball seat or swivel base to permit it to align to suit the stock thickness.

The counter disc with interrupted gear teeth, at the right in Fig. 215, is rather interesting as a part formerly die-cast. A cross-section of it to scale is shown in Fig. 216. It is a white metal alloy squeezed cold from a slug in a 150-ton knuckle-joint press. It is a closed-die operation resembling coining throughout except that the flow is so great as to resemble extrusion. Owing to severity of flow and accompanying tool wear the job may be divided into preliminary squeezing to approximate shape and then final sizing.

TABLE XX

EXPERIMENTAL PRESSURES FOR U. S. COINS

(Tests Made by U. S. Mint, Philadelphia, Pa.)

U. S. Coin	Metal	Total Tons	Tons per Square Inch
Double Eagle	Gold	155	110
Eagle	Gold	110	127
Half Eagle	Gold	60	106
Quarter Eagle	Gold	35	94
Standard Dollar	Silver	160	93
Half Dollar	Silver	140	128
Quarter Dollar	Silver	100	143
Dime	Silver	35	91
Nickel	Nickel	85–90	180
Cent	Copper	40	93

NOTE: The above pressures are reported to be correct within 5 per cent. In the selection of mechanical presses for closed-die jobs, at least double the test pressures. Pressures revised for high relief coins of 1940.

The large plate in Fig. 217 giving an etched appearance is really coined, though not in a closed die. With an area of 10 sq. in. and a thickness of about $\frac{1}{32}$ in. it takes the whole capacity of a 1000-ton knuckle-joint press. It is relatively so thin that a general flow cannot take place, the design being obtained by local movement only.

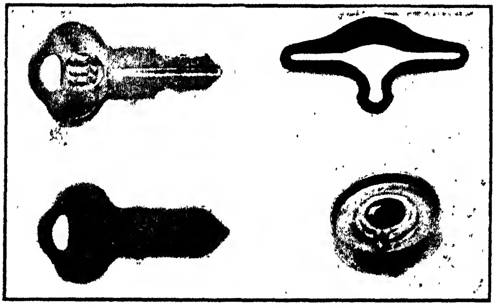


FIG. 215.—Samples of commercial coining: a white metal counter disc, a brass clip and a Britannia metal key blank.

Embossing.—Essentially, embossing involves forming designs on sheet metal in male and female dies without altering its thickness. The work requirement then is merely bending along the lines of the design. In practice, however, few dies are so well constructed with respect to uniform metal thickness that this is true. A possible exception is metal ceiling dies having a hard-steel die and a soft babbitt punch. More often, however, a high pressure must be needlessly exerted over

considerable and unimportant areas in an effort to bring out sharp lines at other points.

The reason for this waste effort and for the difficulty in bringing up sharp corners is illustrated in Fig. 218. In bending over a corner or radius the metal thickness is naturally decreased (Fig. 218 *a*) for reasons explained in the discussion of bending in Chapter V. The sharper the inside radius the greater is the reduction in metal thickness. Accordingly, to make up the deficiencies in the corners, metal must be squeezed out from the flat section. If, as in sketch *b*, Fig. 218, pressure is applied over the whole punch, it is difficult to move the metal and a high resistance is built up. If, on the contrary, the punch is so relieved that pressure is exerted on the metal only at points near the corners to be filled, the necessary movement is easily obtained with relatively little pressure. Based upon relative proportions, sketch *b* (Fig. 218) would require at least five times the pressure needed to bring up a sharp corner by the sketch *c* method, and the result would be no better, if as good.

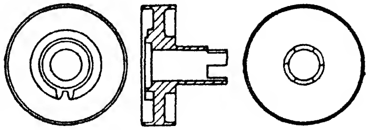


FIG. 216.—A cross-section to scale of the white metal alloy counter disc squeezed from a flat blank.

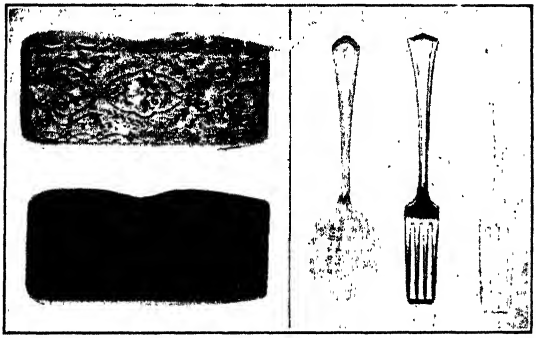


FIG. 217.—Flatware blanks coined in a 400-ton knuckle-joint press and a steel coverplate requiring a 1000-ton press to simulate etching.

Fig. 219 shows a collection of embossing jobs performed in male and female dies. The army button, which for comparison is a 60-ton job, the two brass boxes and the silver and nickel-silver knife handles are all of this type with little attention paid to die relief. The hollow ware also suggests jewelry settings, watch cases, etc.

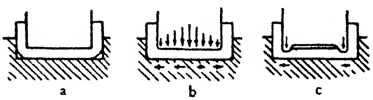


FIG. 218.—Localizing the pressure where it is needed to get a sharp impression.

Such work can take anywhere from 20 to 200 tons per square inch or more, depending upon whether uniform metal thickness is maintained, how sharp an impression is required and how carefully the press

is set up. The wall switch plates at the top are an example of localizing the squeezing area to get a sharp impression without excessive pressure. The punch is relieved as indicated at *c* in Fig. 218 and at *b* in Fig. 189. It strikes only on a line less than 1/16 in. wide and directly

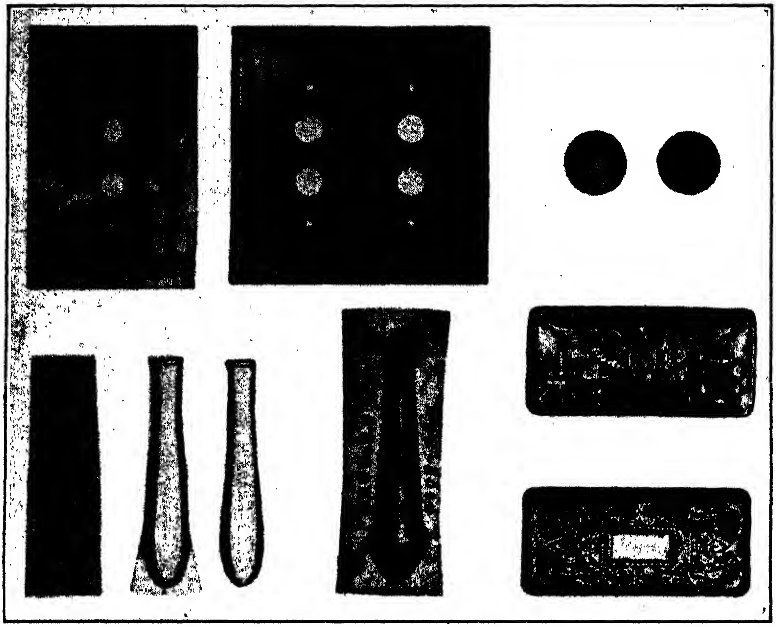


FIG. 219.—Wall plates in brass 100 to 400 tons; copper buttons, 60 tons; hollow knife handles, 250 and 400 tons; box covers in brass, 400 tons.

back of the desired sharp corners. The pressure requirement figures back to about 75 tons per square inch of area actually squeezed. Four hundred tons brings up a better, sharper job than a thousand would give otherwise. The dies are arranged to pinch only and just where the sharp lines are required, and they are relieved elsewhere so that the metal can flow a little and the pressure can be localized.

Die construction must be exceptionally rigid and non-yielding for success in cold-forging and coining operations. The die steel support may be built up from the steel holder with plates of decreasing area and increasing hardness. When breakage occurs owing to side strains in the dies, the steels may be divided into separate pieces along the lines of greatest strain and then forced together under higher than working pressure by means of a shrunk ring or wedges set down into a substantial holder. Steels may be either high-carbon, high-chrome types in small enough sections to harden through uniformly, or medium-carbon, high-chrome alloy steels pack-hardened, and drawn back a little in both cases.

CHAPTER XI

EXTRUSION

Foisy[1] places the beginning of the extrusion of preheated lead and tin in screw-operated cylinders at about the year 1797. This practice developed later into the use of hydraulic presses for hot extrusion of rods, tubes and shapes of varying cross-section in tin, lead, zinc, copper, brass, etc.

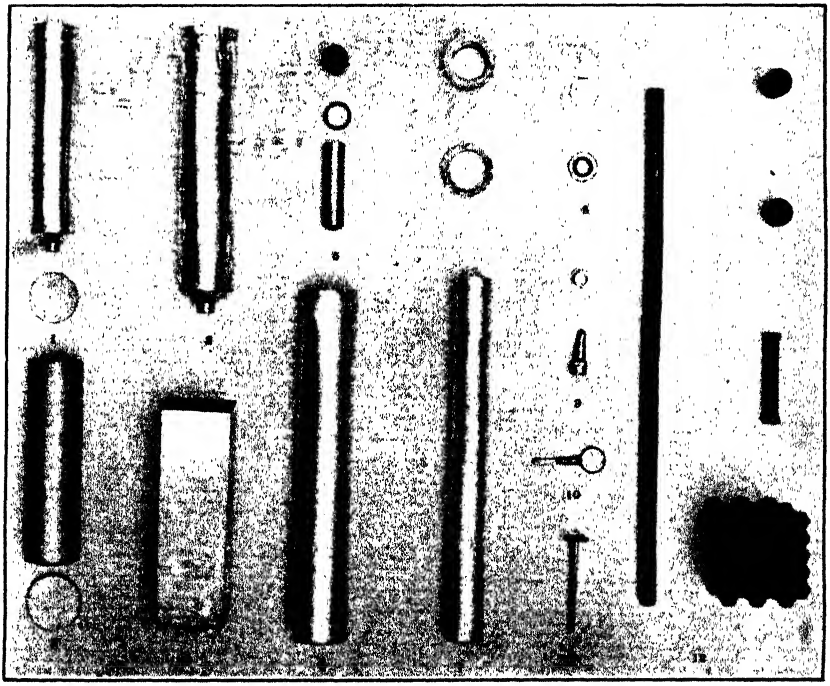


Fig. 220.—A collection of extruded shapes in tin, lead, zinc, aluminum, brass and copper, showing also some of the blanks or cups.

The use of power presses for the extrusion of cold blanks dates from about 1870. The application was the production of tin tooth-paste

[1] G. A. Foisy, "The Manufacture and Application of Extruded Copper Tubes," Trans. A.S.M.E. (1927), M.S.P. 50-9, 93.

tubes. Since then similar methods have been applied to lead and more recently to aluminum. Zinc is extruded usually with a little preheating (say 300° F.), to get a more ductile range (Fig. 130). A modified method of extrusion, typified by the Hooker process, involving relatively somewhat lower stresses, is adapted to the extrusion of brass and copper without preheating. Steel is extruded hot for short distances and cold in the small rivet lugs shown in Figs. 200 and 201.

Fig. 220 is a collection of typical extrusion jobs, showing also the blanks in a number of cases. The metals being worked include lead, parts 1 and 10; zinc, parts 2 and 11; tin, parts 3, 8 and 9; aluminum, parts 4, 6 and 7; brass, part 5; copper, part 12. In general it seems necessary to use relatively pure metals especially when dealing with those subject to strain hardening. Thus for part 12, electrolytic copper is specified and required to be at least 99.90 per cent pure. For part 7 the aluminum is better than 99.6 per cent pure. For part 2 very pure "Horsehead" zinc is used. Part 5 is extruded from the same 70 : 30 cartridge brass used in the drawing process, the analysis of which permits iron up to 0.050 per cent, lead up to 0.070 per cent, other impurities up to 0.150 per cent, copper 68 to 71 per cent and the balance zinc.

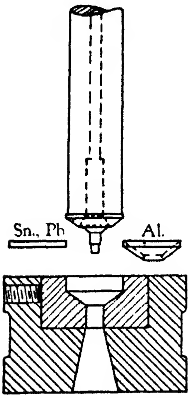


FIG. 221.—A typical collapsible tube die and the outline of blanks used in it.

Collapsible tubes, parts 1 and 3, and the caps for them, parts 8, 9 and 10, are extruded from tin, lead and aluminum according to their purpose. A typical tube die and punch is illustrated in Fig. 221. Note that the punch is under-cut above a narrow shoulder and that the die is very shallow compared to the length of the tube extruded in it. The die is as thin as possible to permit hardening clear through, and is mounted in a substantial holder. The surfaces which control the flow of the metal up around the punch must be carefully polished in the direction of flow. Tin and lead slugs are blanked out flat. Aluminum slugs are usually cupped in the blanking operation, and the outer edges are burnished, to ease the starting of the flow. These blanks are also pierced in some cases to allow flow into the neck as well as out to the wall, thereby slightly reducing the accumulated pressure on the tools.

In production, the blanks are cut or cut and formed, preferably in multiple dies six or eight per stroke in fast automatic feed presses. Aluminum blanks are then annealed (tin and lead anneal below normal

room temperatures). The blanks may be fed by hand or automatically by coin feed or hopper feed to the extrusion die. As the pressure is applied the metal squirts up around the punch, which must be accurately centered. A cam-actuated knockout in the die assists the tube to stay on the punch as it rises clear of the die. Some extrusion presses have strokes over twice the length of the tube permitting it to be stripped in place. Most of the collapsible tube presses, however, have short strokes, and the punch after rising clear of the die swings or slides for-

Fig. 222.—A series of hopper-fed collapsible tube extrusion presses shown prior to installation of air ejection methods. (*Courtesy of Sun Tube Co.*)

ward to a position where the tube may be stripped off by hand or blown off by an air jet through the punch. Later the tube is trimmed on both ends and the thread is cut, all in a little high-speed trimming lathe.

Fig 222 shows a line of automatic presses in an efficient tube plant. The picture was taken shortly before the installation of an air stripping and automatic conveying system releasing the operators for other work. The presses are rather heavy, of the eccentric shaft, shrunk tie-rod type, and built so substantially that the amount of surplus tin lost in the end of the tube is held to a very small percentage. The drive of these

presses includes the patented "beaver-tail stop" mechanism which brings the punch to rest just as it reaches the metal, in an effort to remove the contact shock. It then accelerates and performs the extrusion at an almost uniform rate to distribute and ease the severity of flow. Fig. 223 shows a comparison of the theoretical working period of this modified crank motion, with that of the knuckle-joint extrusion presses, Fig. 224, and the plain crank-motion tube presses. Note that, although the strokes and operating speeds of the presses are taken the same in each case for comparative purposes, the actual working period is longest in the case of the modified crank.

Returning to Fig. 220, parts 5, 7 and 12 are produced by the Hooker process, a patented method of extruding and trimming. Instead of squirting the tube up around the punch by pressure on the bottom as before, this method involves squirting down through the die by pressure on the wall or flange as illustrated in Fig. 225. A suitably shaped and annealed shell or cup is carried into the extrusion die. The pilot or nose of the extrusion punch, *e*, acts as a mandrel to control the wall thickness of the tube. Consequently, in the extrusion of the cartridge case part 5, it is possible by suitably tapering the mandrel to obtain in a single stroke a case with a wall which is thin at the top and thick toward the bottom as in drawn and ironed cases, Figs. 146 and 154. The extruding punch and trimming punch are mounted on a slide which shifts to permit first one and then the other to enter the die. After extrusion the tube remains in the die. On the next stroke the trimming punch enters to push the tube through the die and lift the ring of scrap out to be stripped off outside of the die. The blank or cup and the ring of scrap are shown with tubes 5 and 7 in Fig. 220.

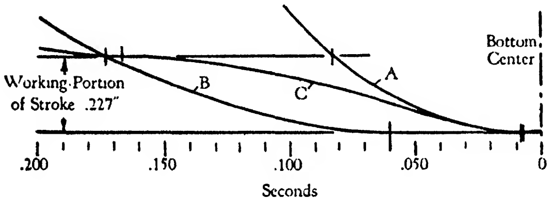


FIG. 223.—Time charts of the extrusion period of a crank press (*A*), a knuckle-joint press (*B*) and a modified crank press (*C*), showing the increased time allowed for the extrusion operation without increase in press speed.

The blanks are prepared either from thick sheet metal, blanked, drawn, coined to thin the bottom and set down the sides, and finally annealed; or from slugs sheared off from a rod four or five per stroke. These are first indented in a preparatory coining operation, then annealed, then finish-coined and reannealed ready for extrusion.

Group 12 in Fig. 220 shows the steps in the production of certain cooling and condensing radiators and blast heaters. Half-inch diameter

extruded electrolytic copper rods are cut up into 7/16-in. lengths. These are squeezed into suitable thin-bottomed cups in two operations with two anneals to counteract the resultant strain-hardening of the material. The cups, measuring 9/16 in. in height, 7/16 in. in diameter and 0.100 in. in wall thickness, are extruded without preheating into tubes 9 to 15 in. long, 0.276 in. in diameter and 0.0035 to 0.006 in. in wall thickness. The operation is performed in small (No. 52), straight-sided presses running 125 SPM equipped with two sets of tools so that one tube is being extruded each stroke and another tube trimmed. The work must be performed quickly to avoid excessive pressures, but on account of the heat generated the tools must be flooded with lard oil, which serves both as coolant and lubricant. The tubes are then sawed up into short lengths and the ends expanded for assembly into radiators.

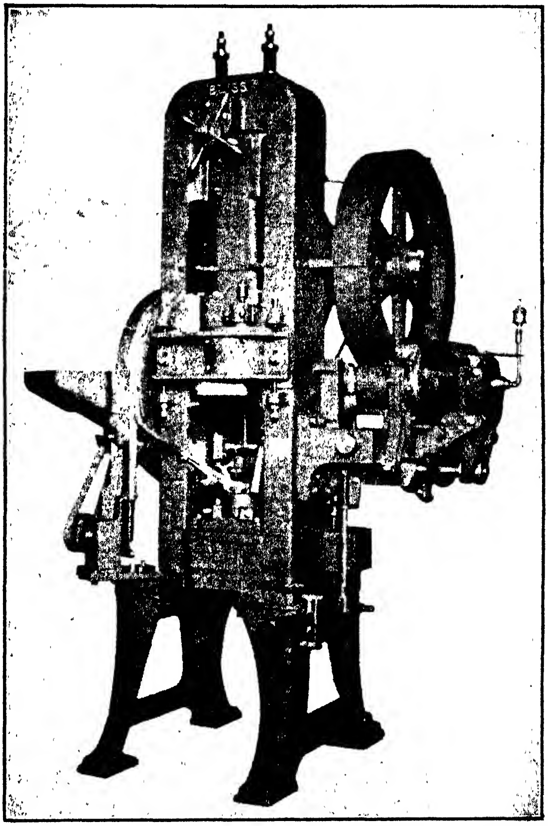


Fig. 224.—A typical collapsible tube press of the knuckle-joint type with hopper feed and automatic swinging arm punch holder.

In good practice the extruding face of the punch is not flat but tapered at an angle of about 20°. The step in the die is on about a 30° bevel, as indicated in Fig. 225. The flatter the punch angle and the steeper the die angle, the easier is the extruding action. The angles mentioned above are a compromise with the scrap loss. The relation between the wall thicknesses of the blank and tube is limited approximately between 25 : 1 and 4 : 1.

Of the small parts shown in Fig. 220, parts 8 and 9 are tin collapsible

tube caps, part 10 is a lead tube stopper and 11 is a zinc nail. Part 8 is extruded from a flat blank with threads complete, as indicated in Fig. 226. Serrations or flats about the circumference prevent the cap from turning as the mandrel revolves to unscrew it after extrusion. Note in Fig. 226 that the volume of flow in both the cap head and the nail head tends to leave a mark or depression on the surface. For this reason, a bead or design frequently is arranged to cover or disguise it. Part 9 is extruded or swaged from a previously prepared cup. Part 10 is extruded sidewise from a round lead blank.

Fig. 227 shows the manner of flow of metal extruded through an orifice, such as in the case of the zinc nail, part 11 in Fig. 220. The illustration developed by Colombel[2] was the result of compressing

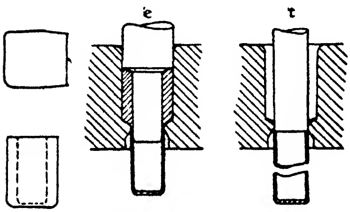


FIG. 225.—Extrusion by the Hooker process, in which alternately the extrusion punch *e* and the trimming punch *t* enter the same die. See page 258.

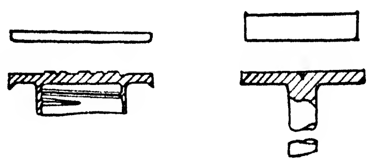


FIG. 226.—Cross-sections of parts 8 and 11, Fig. 220; a tube cap and a nail respectively showing flow marks on their top surfaces.

a cylinder formed by two iron discs 50 mm. thick and 150 mm. in diameter through a concentric circular orifice 48 mm. in diameter. This cylinder was heated to a bright red and subjected to blows of a hammer. The third blow of the hammer broke the die, but the discs had already been extruded to the point shown. It is of interest to note that the joint between the two discs has changed from flat to conical, following the flow lines. It is also reported, as might be expected, that lead flowed in practically the same manner as the iron.

Theoretical data having to do with computing extrusion operations are still rather scarce. A discussion in Chapter X (Fig. 188) brought out some reasons for rising pressures in squeezing thin sections or parts where the flow is restricted. Plastic flow begins when the yield point of the material is exceeded, and, as illustrated in Figs. 184 and 185, the yield point depends upon the amount the metal has been cold-worked (strain-hardened) since its last annealing. The pressure will rise comparatively little as the die fills to the point where the metal begins to

[2] C. A. Colombel, "The Extrusion of Metals," *Rolling Mill Journal*, May, June, July, etc., 1931.

flow through the orifice between the punch and die. The flow resembles that of a very viscous liquid, although the metal retains its crystalline structure, and except for lead and tin the flow is undoubtedly the slip-plane movement of cold-working rather than the amorphous rolling of whole crystals which characterizes hot-working (above the annealing or recrystallization temperature). The heat generated in the operation undoubtedly reduces the operating pressure, but whether it is sufficient to induce spontaneous annealing in metals with annealing points as high as brass, copper or aluminum seems doubtful.

In this connection Foisy[1] points out that although extrusion of copper in a quick-acting power press is commercially satisfactory, the same tools were invariably broken on account of excessive pressures in a hydraulic press acting at one-seventieth the speed. It is his belief that the heat generated in extrusion materially increases the plasticity of the metal and reduces the strain on the tools. Ample coolant must be used, however, to prevent the tools becoming too hot.

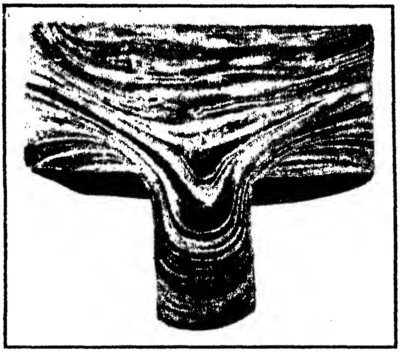


FIG. 227.—Flow marks in iron extruded hot through an orifice. (Colombel.)[2]

He states that experiments carried on in an Olsen testing machine showed an initial pressure of 50,000 lb. to start the flow, dropping at once to 10,000 lb., which, he argues, shows that energy has been converted into heat. As the plan area of the cup is nearly 0.1 sq. in. this indicates an initial pressure of 250 tons per square inch followed by an extruding pressure of 50 tons per square inch.

Fig. 228 shows a 500-ton relatively fast operating extrusion press used on the larger flat-bottomed aluminum tubes on the order of parts 4 and 6 (Fig. 220). This is a relatively more severe operation than that performed on the copper cups, yet the press selection is based on around 50 tons per square inch of squeezing area. The yield point of the annealed blank is likely to be under 3 or 4 tons per square inch, but the orifice is small compared with blank thickness. The tubes strain-harden materially in extrusion in spite of the heat generated in the moving metal.

The basis for press selection in the extrusion of tin and lead tubes is about 60 to 80 tons per square inch. As very little coolant or lubricant

[1] *See* footnote, p. 247. [2] *See* footnote, p. 252.

can be used, heat generated in extrusion limits operating speeds to 40 to 45 SPM for the sake of the tools.

Part 2 in Fig. 220 shows an extruded zinc shell. The operation in this case is performed in a quick-acting eccentric shaft press with the blank preheated to appreciably above the annealing point. Fig. 229 shows the pressure curve obtained in extruding these shells experimentally with heated tools and blanks at about 400° F. in an Olsen testing machine. The yield point of the zinc was undoubtedly under 6 tons per square inch, yet extrusion did not start until the pressure reached 25 or 30 tons per square inch. Owing possibly to overcoming some surface-tension effect there was a small drop in pressure as the movement started. The final rise in pressure to 35 or 40 tons per square inch is probably explained by the decreasing bottom thickness. The intermediate rise which appeared regularly is difficult to explain.

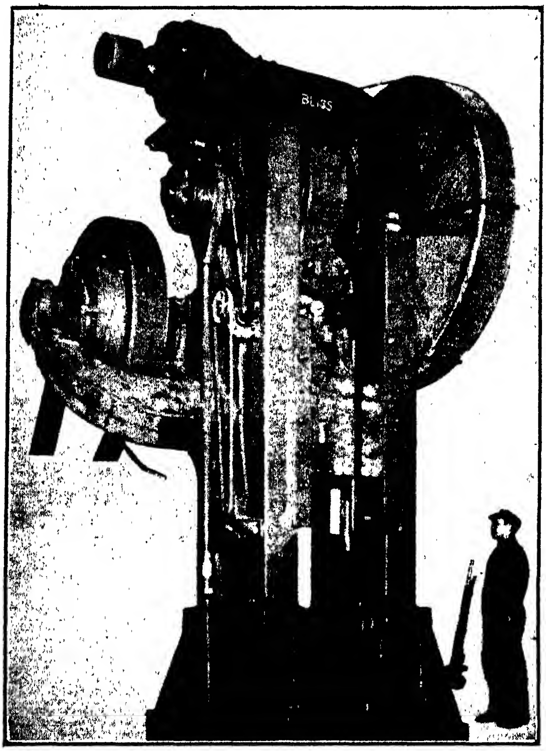


Fig. 228.—A relatively fast-acting eccentric shaft press used in the extrusion of the larger aluminum shells.

It is interesting to note that both extruded battery cases and extruded cartridge cases are reported to be more satisfactory than the drawn article. It is apparent, of course, that the extruded shell must have a uniform wall thickness vertically and uniform grain structure. The drawn shell, on the other hand, is strain-hardened toward the top edge and increased in thickness there, unless it has been ironed. It also has been subject to thinning at the bottom radius for each reduction.

Fig. 230 shows a micrographic study of a cross-section of the extruded 70:30 brass cartridge case shown at 5 in Fig. 220, which cor-

responds in size and stage of completion to the drawn and ironed case examined in Fig. 155. This is especially interesting as it affords a direct comparison of the extruded structure with that of the drawn shell. The details of treatment of samples are the same in both cases. The photomicrographs *A* and *C* in Fig. 230 show metal in the bottom of the shell, before and after annealing, respectively. Photos *B* and *D* are typical of the full length of the side-wall section, before and after annealing, respectively.

The plastically worked side-wall (*B*) is the most interesting, of course. After working, which amounts to an elongation of, say, 600 per cent, it shows a uniform structure without evidence of overstrain fractures or even of slip planes though it was examined also at 200 magnifications. The dark and light streaks down the center seem to be identifiable as the much-elongated old dark and light crystals. This structure merged quickly at the bottom corner of the shell, into large old grains showing numerous strain lines and then into the largely unstrained grains shown at *A*.

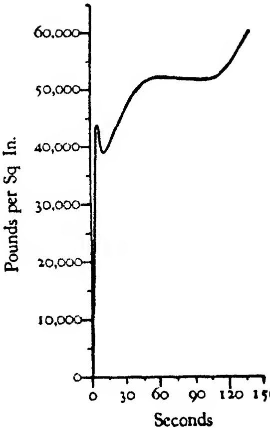


Fig. 229.—Pressure curve from the experimental extrusion of warm zinc in a testing machine.

An anneal of 7 to 8 minutes at 1300° F. changed the extruded structure *B* to the equiaxed and unstrained structure *D* without apparent evidences of residual directional properties. A larger annealed crystal size resulted after extrusion than after drawing (Fig. 155) with an identical anneal. The explanation would seem to be that the more severely worked material began to anneal at a lower temperature, permitting a greater growth in the time allowed. The extruded structure was much harder than the (extra-hard temper) drawn wall structure, but in the soft state, after annealing, there was little to choose between them.

Foisy [1] claims that copper comes from the long extrusion shown at 12 in Fig. 220, in practically an annealed state. If so, this may be due both to the extremely low rate of strain-hardening for copper and to a very high operating temperature resulting from fast operation and a long extrusion. Tin and zinc crystallize in lattice patterns which are not favorable to cold-working, but, as tin (and lead) recrystallize below room temperature, at which they are worked, and zinc below 300° or 400° F., at which it is usually extruded, they are all really in their

[1] See footnote, p. 247.

hot-working range and subject to what has been described as spontaneous annealing. Aluminum and brass show distinctly the effects of severe cold-working, and must be annealed both before and after the extrusion operation if ductility is required in the finished product.

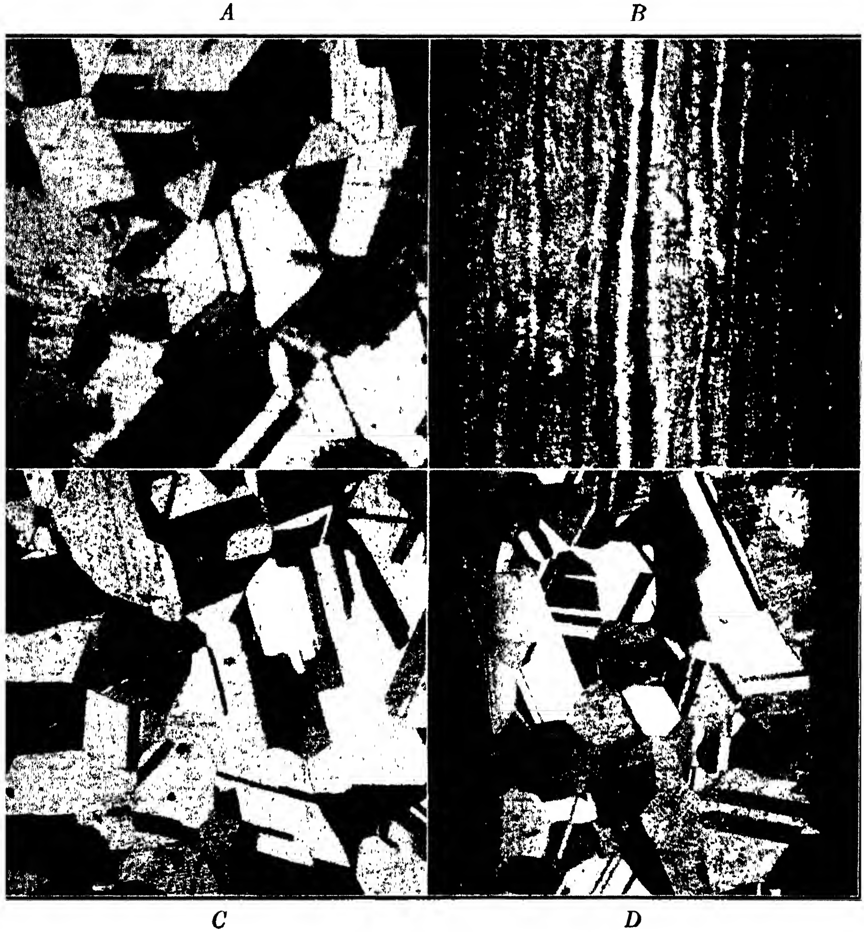


FIG. 230.—Extruded cartridge case, ×100, showing the bottom, *A*, and the wall, *B*, as extruded; the bottom, *C*, and the wall, *D*, after annealing.

Squeezing the bottom of a shell to force metal there to flow up around the punch (Fig. 221) requires greater unit stresses than does squeezing a thick side-wall vertically to flow the metal down into a thinner wall, as in the Hooker process, Fig. 225. The explanation is that in the first method the metal must move a greater distance to reach the orifice than in the second method, and also that the pressure tends to pyramid

in the center as the blank becomes thin relative to its diameter. This difference in severity between the two methods is borne out by the fact that the first method, which permits the use of a simple blanked slug, is used for the softer metals, whereas the Hooker process, which requires two or three operations and anneals to prepare the slug, is used especially for copper and brass.

It is interesting to note that work is being done by several investigators on a method of extruding cast slugs, on the theory that the refinement of the cast structure, accomplished by extruding it, is ample in itself without the preliminary refinement of rolling. On the side of economies, the cost of casting, cropping and cleaning many small blanks must be set against the quantity-production advantages of rolling a billet and cutting the blanks in multiple in fast presses. For the low-melting-point metals this objection has been overcome by a patented process of casting the molten metal directly upon the surface of a chill roll, passing it between that roll and another for gauge, carrying it in an endless strip through a multiple die blanking press and carrying the scrap directly back into the melting pot.

It seems logical to examine certain laws of hydraulics in the theoretical consideration of extrusion. Fast action is desirable in extrusion because of generation of heat, and yet an increase in speed of flow must be accompanied by an increase in the tool pressure causing that flow. In hydraulics, the velocity of flow of water through any orifice or opening of fixed shape and size is determined by the "head" or pressure causing the flow. For liquids, the theoretical pressure inside the orifice is equal to the density of the liquid times velocity of flow through the orifice, squared, divided by $2\,g$. Obviously the result is not directly applicable to solids forced to flow plastically, owing to greater internal friction (cohesion or interatomic attraction), but the indicated rise in pressure according to the square of the velocity for a given orifice and a given plastic state (or yield point) may apply.

A stream of water flowing from a sharp-edged orifice near the bottom of a vessel is found to contract in diameter for a short distance beyond the orifice and then to expand. Quite advantageous results have been obtained by shaping a tubular orifice with reference to this natural contraction. A similar contraction is found in extrusion. Thus a tube extruded up around the punch is neither as large in outside diameter as the diameter of the die, nor as small in internal diameter as the diameter of the punch. The wall thickness is less than the clearance between the punch and die which governs it. This difference may be changed by changing the shape, especially the sharpness of the corners over which extrusion takes place. Stream-line principles for easy flow

and the avoidance of retarding eddy currents may also be remembered in this connection.

Erosive action in the rapid flow of fairly hot metal over a narrow-edge area necessarily limits the life of extrusion tools. Modern high-alloy steels have considerably improved the average results, and the use of chromium plating to give a thin, hard wearing surface which is renewable has proved of considerable value in some instances.

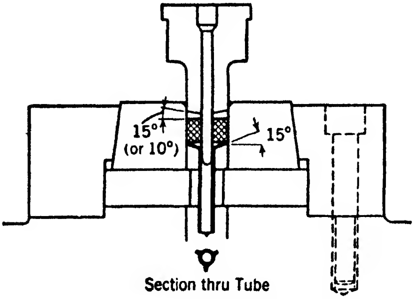


FIG. 230 *A*. — A push-through extrusion die for a ribbed aluminum-copper alloy tube. Approximate tube dimensions ⅛-in. I.D., 0.020-in. wall ¼-in. overall diameter.

Referring back to the mechanically difficult, alternate use of two punches (extruding and trimming) in Fig. 225 for push-through extrusion, note the alternative scheme shown in Fig. 230 *A*. Here the slugs are fed into the die in continuous succession, each new one forcing the previous one out ahead of it. Trimming may be handled with band saws, rubber wheels, etc. Slugs may be pierced, extruded or solid to suit the job. The successively extruded tubes or shapes, separated by a film of lubricant, may be broken apart easily for trimming. It is open to experimental development on the particular job whether the angles on the punch face and die seat should be the same (both 15° in Fig. 230 *A*), or whether the die seat angle should be a little greater to feather the trailing edge of each tube.

CHAPTER XII

HOT PRESS FORGING

The ancient art of forging required a fire, an anvil, a sledge and plenty of muscle. Increasing size of work brought about the development of the mechanical hammer, the steam hammer and the hydraulic forging press. Greater quantities of identical parts to be produced brought forth the board lift drop hammer, the steam drop hammer, the percussion press, the forging mill, the forging machine and the forging press.

In the quantity-production group, the drop hammer handles the greatest range of shapes in that the system of turning the work from side to side under repeated blows permits forming plain bars to fit odd shapes with little scrap loss. Operating economies seem to have given this field largely to the board lift type of hammer.

The other machines get away from the shock of the falling weight required by the drop hammer and, for most of their range, finish a part in a single motion, whereas usually the hammer must strike a number of blows. The power screw press or percussion press is a modification of the drop-hammer principle with the shock reduced. A flywheel at the top of the screw is brought up to speed by a friction drive, and all the energy so developed is absorbed in doing the work, just as all the energy of the falling weight is absorbed in the drop. The flywheel must then be reversed to lift the ram to the starting position.

Fast-acting forging machines, Fig. 231, and forging presses, Fig. 232, which have much in common absorb only a small part of the energy of a continuously running flywheel during the working period. They differ in that the forging machine is regularly horizontal and adapted to operations on or from the bar, whereas the forging press is vertical as a rule and is generally used for forging blanks or slugs previously cut to size. Either type can be arranged for multiple operations with suitably developed tools.

The fastest action of all, from the standpoint of production, is obtained in forge rolling, in which a hot bar passes through rolls having the developed shape of the part sunk in their surfaces. This method is also the most limited in application by reason of scrap loss, roll cost and relative uniformity of shape required.

Hot-Working Metal.—We have already defined the hot-working of metal as working it at temperatures above that of recrystallization or annealing. This was shown to be rather a range of temperature, depending upon time of anneal, previous condition and severity of previous treatment of the metal, all of which was discussed in some detail in Chapter VII. Table XII gave the minimum temperatures at which various metals begin to recrystallize, and Figs. 127 and 131 showed the

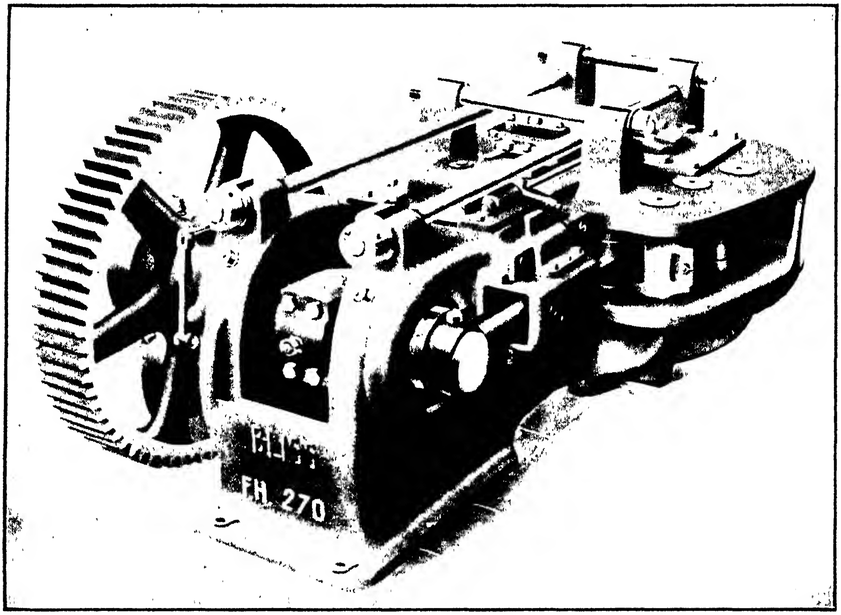


FIG. 231.—A typical forging machine, principally for small steel parts produced from bar stock.

disappearance of strain-hardness of brass and nickel, respectively, as they pass through the recrystallization range.

Forging requires considerable working of the metal. If the average forging operation were attempted cold, the metal would strain-harden sufficiently to cause fractures in itself and to damage the tools by excessive pressures long before completion of the flow. Accordingly, metal is forged at a temperature [1] sufficiently above that of recrystallization so that annealing approximately keeps up with strain-hardening. This strain-hardening itself occurs less and less rapidly as the temperature increases. Above the annealing temperature it is probably further reduced, in testing and other slow actions, by an "amorphous" inter-

[1] Approximate forging temperatures, Table XXVII, p. 432.

crystalline movement in which the resistance to working increases with the speed.

As metal is heated it expands and becomes more mobile. The forces holding it intact and resisting deformation become less, as in Table XXI, for steel. In the individual atom the acquisition of energy in the form of heat increases the amplitude of oscillation of the electrons of which it is made up. This increases its size and the distance between atom centers in the individual crystal, with a proportionate loss in cohesive forces.

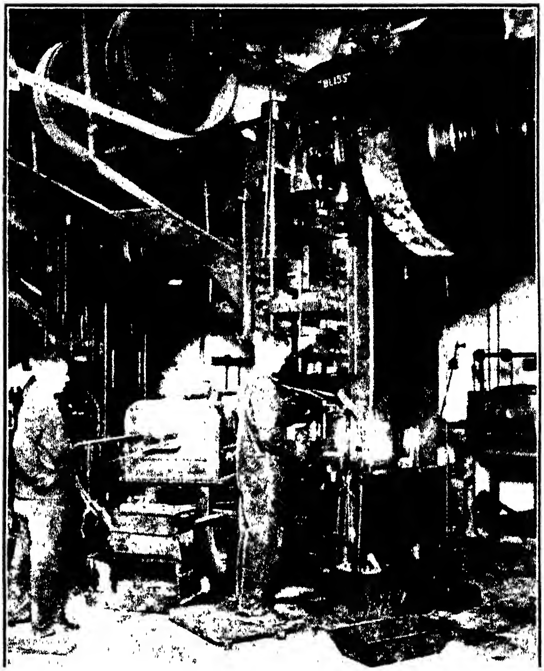


Fig. 232.—A forging press producing brass forgings from sawed slugs, finishing between 600 and 700 pieces per hour.

The crystalline structure disappears entirely at the melting point, and approaching it the forces between atoms and between crystals become progressively less. The change is not uniform, as indicated by the temperature plasticity curve for zinc, Fig. 130, and by the forgeability curves of Fig. 239. By way of explanation, note that steel changes structurally from the body-centered cubic to the more plastic face-centered cubic crystal lattice above 900° F. Along the boundary between alpha and beta brasses the former changes to the latter as the temperature rises. In steels having a carbon content between 0.02 and 0.12, and in some other metals, there is a temperature point, controlled by the state of strain-hardness, at which a rather violent form of grain growth takes place (germination, Table XVII).

Speed and Resistance.—With regard to the use of test results for the prediction of stresses in hot-working, it should be noted that time has considerable effect, so that testing equipment should simulate working conditions in speed of action. Thus the New Jersey Zinc Company

showed that ductility tests for drawing zinc were misleading unless performed at approximately press drawing speeds. Zinc anneals at or near atmospheric temperature, so that most operations on it are performed in the "hot-work" range.

TABLE XXI

NOMINAL TENSILE STRENGTH OF STEELS, HOT[a]

See also Fig. 133*a*.

Degrees F.	Unit Stress, Pounds per Square Inch, for Several Carbon Contents:				
	0.05-0.15 C	0.30 C	0.50 C	0.75 C	1.00 C
2200	2,250				
2100	3,500	4,000			
2000	4,500	5,000	5,600	6,500	
1900	5,100	5,800	7,300	8,800	13,000
1800	5,800	6,700	8,800	11,000	17,000
1700	7,000	8,600	10,700	13,800	23,000
1600	8,600	10,000	12,500	15,600	31,000
1400	12,600	14,000	15,500	17,000	
1200	18,000				
1000	25,600				
Cold 60	50,000	70,000	85,000	100,000	120,000

[a] After E. Kieft, "Rolling Mill Analysis," Proceedings of the Association of Iron and Steel Electrical Engineers, 1929–30, p. 438.

In *cold*-working steel, movement takes place along slip planes through the crystals, and the forces are said to be unaffected by speed changes in the test or work range. (This applies also to common test properties, with the exception of general elongation, which does change with test speed.) Only in the case of an infinitely slow fatigue failure do we get intercrystalline movement. Here the break follows the weaknesses of the grain boundaries, and the strength of the material is recorded appreciably lower than by normal speed tests. Above the annealing temperature, however, it seems possible to work the metal sufficiently slowly so that the movement will follow the grain boundaries as in a fatigue break. Increasing the speed (as to that of a testing machine) apparently causes some of the movement to follow slip planes through the crystals instead of working around them. This naturally somewhat increases the resistance to movement.

Fig. 233, according to Professor Trinks,[2] illustrates the increase in resistance or strength of hot metal with increase in working speed up to a certain point, beyond which the resistance remains constant in spite of continued increase in working speed. According to foregoing discussions, it seems possible that at this point the movement is fast enough to become entirely transcrystalline and therefore unaffected by speed. Professor Trinks points out that rolling operations are normally above the point where speed makes any difference in load, and this is undoubtedly true of most forging operations.

Temperature Change in Working.—Professor Trinks also speaks of the actual generation of heat in the process of working the metal. We know that some heat is generated in cold-working operations, for blanks, drawn shells or extruded tubes produced continuously from cold strip or blanks come out warm to hot, depending upon speed and severity of the operation. Reasons offered include surface friction, internal friction and the application of pressure. The latter two probably amount to about the same thing, as the application of sufficient external pressure is the cause of internal movement. We are told that increasing the temperature of a block of metal by application of external heat results primarily in increased vibration of electrons. It seems probable that sudden internal movement should also cause an increase in vibration of electrons, which would be evidenced by increased temperature. And increased speed of operation should result in greater generation of heat which seems to be borne out in practice. This internal generation of heat is often sufficient to be of appreciable value in cases of severe flow and in a series of operations following one another in close succession.

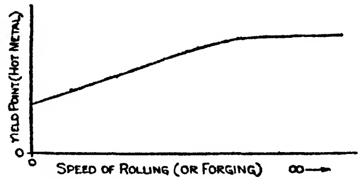


FIG. 233.—At normal working speeds the hot-working stress is little if at all affected by speed, probably because the action is too rapid to permit intercrystalline movement. (*Curve after Trinks* [1]) *See also* Fig. 133*a*.

We know that heat must be applied in melting (metal, ice, etc.) and that heat is given off in crystallizing or solidifying. The same relation applies to vaporizing and condensing, respectively. Can we not also state that heat is always generated or given off in working or strain-hardening a metal? Conversely, we know that heat must be applied to the metal to anneal it or permit it to rearrange in unstrained crystals.

Most forging is done at speeds which cause movement along slip planes through the crystals which must result in strain-hardening. But

[2] W. Trinks, "Roll Pass Design," *Rolling Mill Journal*, Feb., 1929.

as the temperature is raised this movement is easier and the strain-hardening is less severe. And as the temperature is raised, annealing takes place more quickly until a balance is reached where in hot-working the strain-hardening is corrected instantly or nearly so. "Spontaneous annealing" some have called it.

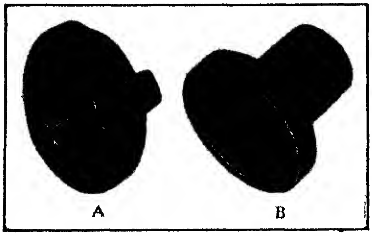


Fig. 234.—Two similar and fairly severe brass press forgings in which speed of action made the difference between chilled failure and success.

Chilling.—There is another abstract time element in forging having to do with the rate at which dies will conduct heat away from a thin or light section of hot metal. In a drop-hammer operation, it may often be noted that some portion of the forging surface will show relatively dark just as the hammer is rising but will quickly return to bright as it draws heat from some heavier portion.

The greater the temperature difference between the forging and the die, the faster is the heat transfer and the greater the chance of chilling. Accordingly, some press-forging concerns follow the practice of laying a hot chunk of metal on the dies in the morning to warm them up before starting and depend upon the work to keep them warm in operation. Others play a gas flame on the dies, as in Fig. 232.

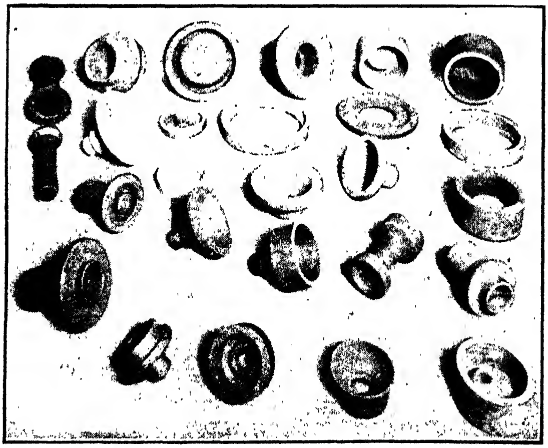


Fig. 235.—A group of large press forgings produced principally in hydraulic presses.

The faster the action of the press the less time there is for the dies to draw heat from the work. Parts *A* and *B* in Fig. 234 are two fairly similar brass press forgings of about the same weight. Part *A* was first produced experimentally in cold dies in a 350-ton press at about 25 SPM. The surface was not especially good, and the lower end, which was down in the die, was badly cold shot and did not fill. Part *B* was actually more severe in depth and thinness and in fine lettering on the

surface. Yet it was produced with an excellent finish in only a 200-ton press operating at between 60 and 70 SPM.

The smaller the piece the less heat it will hold and the faster it should be handled for satisfactory results. The smaller forging presses now operate at 80 to 100 SPM and even faster.

In forging the several metals, steel is necessarily the most severe upon the tools. Brass is materially easier to work and is the metal most commonly press forged. Copper, aluminum, "duralumin" and zinc are also handled, though less commonly.

Press Forging Steel.—Fig. 235 shows a typical collection of hydraulic press forgings. These take from one to three operations to draw up from a disc or to extrude or forge from a cylindrical billet. Some of the smaller ones are typical also of mechanical press forgings, which run from 15 or 20 lb. each down to automobile valve heads and similar small parts weighing a few ounces.

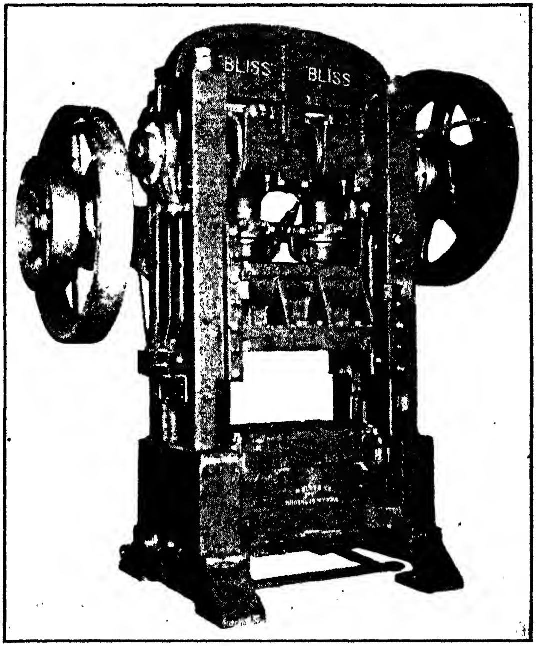


Fig. 236.—A typical double eccentric forging press as used in the production of railroad supplies.

It will be noted that the characteristic shapes are round and fairly simple. Round dies are cheaply made and easily redressed, points which are economically important on account of the heat and scale involved in forging steel, which reduce the life of delicate dies to a fairly low point. Frequently, pieces which are bulky enough to hold the heat are put through a number of operations in a series of presses or through several dies arranged in the same press using such a machine as is illustrated in Fig. 236.

Such presses and combinations of presses are used, for example, in the forming of numerous railway track braces, switch and signal parts, automobile bumpers and other parts. In such cases a man will be

assigned to the furnace and another to each transfer position. This may mean several men per press, working both at the front and back. With the equipment running steadily at, say, 60 SPM for fair-sized forgings, the men will catch every stroke on each operation, averaging 45 or 50 pieces per minute all day. This includes 15- or 20-minute rest periods every hour or so, during which a maintenance gang checks up the tools. The operations include hot bending, piercing and trimming, as well as forging.

Another and similar application, except with one man per press for a series of operations, is found in the production of picks, hammers, axes, etc. Fig. 73 shows the tools and operations involved in pick-eye forging. The outside slide on the left end of the press is used for three preliminary operations to shape up the center of the bar. The eye is then pierced and worked out in gripper dies in three stages. The amount of scrap lost in this operation is remarkably little, as tapered punches work most of the displaced metal out into the wall of the eye. The points of the pick are worked out subsequently in a helve hammer.

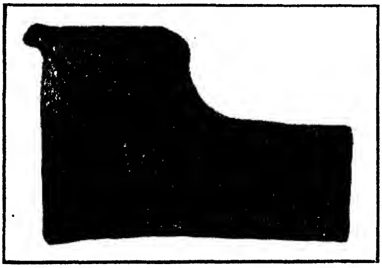


Fig. 237.—Flow lines in the metal brought out by etching.

In the production of claw hammers, peen hammers, etc., a similar method is followed. The part is blocked and the eye forged in the press. A drop hammer finishes the shape, and a trimming press with outside slide trims the flash, pierces and finish-swages the eye. The three-man gang includes the hammer man, who strikes and restrikes the piece and tends the furnace; the press man, who sets the pace, catching almost every stroke at 60 SPM for four to six forming blows per forging; and the boy on the trimming press with two or three operations to do.

Fig. 237, a piece of press-forged steel etched to show the flow lines, illustrates the manner in which the metal is made to fill and follow a shape. It also illustrates a seam which might, under some circumstances, prove objectionable. If so, a preliminary forging operation would be required to upset that amount of metal without a wrinkle.

Rules governing upsetting operations were clearly and simply stated by E. R. Frost [3] in a paper before the American Drop Forge Association.

1. The limit of length of unsupported stock that can be gathered or

[3] E. R. Frost, "Laws Governing Forging Machine Die Design," American Drop Forge Association, reprinted by National Machinery Company, Tiffin, Ohio.

upset in one blow without injurious buckling is not more than three times the diameter of the bar (Fig. 238 *A*).

2. Lengths of stock more than three times the diameter of the bar can be successfully upset in one blow (in a closed die), provided the diameter of the upset made is not more than one and one-half times the diameter of the bar (Fig. 238 *B*).

Therefore in forging to larger diameters it is necessary to use two or more operations (Fig. 238 *C*).

3. In an upset which requires more than three diameters of stock in length, and in which the diameter of the upset is one and one-half times the diameter of the bar, the amount of unsupported stock beyond the face of the die must not exceed one diameter of the stock (Fig. 238 *D*).

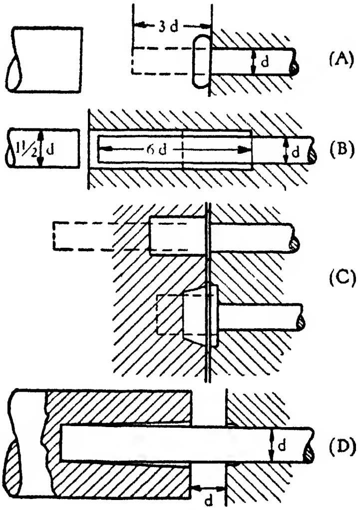


FIG. 238.—Recognized limits upon amount of metal and tool dimensions in successful upsetting. (*After Frost*[3])

Although these rules were apparently stated in a discussion of forging steel they may be applied equally well to other metals.

Forging Non-ferrous Metals.—Fig. 239 shows a series of curves giving the relative forgeability of the non-ferrous metals, according to the experiments of W. L. Kent.[4] Slugs ½ in. in diameter and ½ in. high (and 1 in. by 1 in. for lead) were carefully annealed, then heated to the various temperatures, held there 15 to 25 minutes and then subjected to a uniform blow of 50 ft.-lb. in a small drop hammer. The amount that the slug was squeezed down under the blow was plotted to indicate forgeability.

Note that the temperature range through which the metal flows easily is relatively narrow for both the copper and alpha or high brass, with corresponding danger of overheating. Neither of these metals is forged in anything like the volume of the easily worked beta brass.

In forging copper, every possible precaution should be taken to hold down the formation of the hard black oxide, which has a serious erosive action on the dies. This and the relatively high forging temperature help to account for the volume of copper now forged cold.

[4] W. L. Kent, "The Behavior of Metals and Alloys during Forging," *Journal of the Institute of Metals*, London, 1928.

Table XXII shows a rather interesting comparison of the hardness of copper after hot forging at different temperatures and after cold-working corresponding amounts with and without annealing. The table shows Brinell hardness measured with a 1-mm. ball and a 10-kg. weight for 30 seconds. Copper recrystallizes between, say, 400 and 600° F., according to the time allowed and previous strain-hardening. Yet in the first instance, where the metal was probably cold-worked under 20 per cent, it did not recrystallize in 10 minutes at nearly 600° F. The slugs which were forged at the lower degrees of heat show considerable residual strain-hardening. Above 1100° F., however, the annealing was either spontaneous or nearly so, and was completed before the

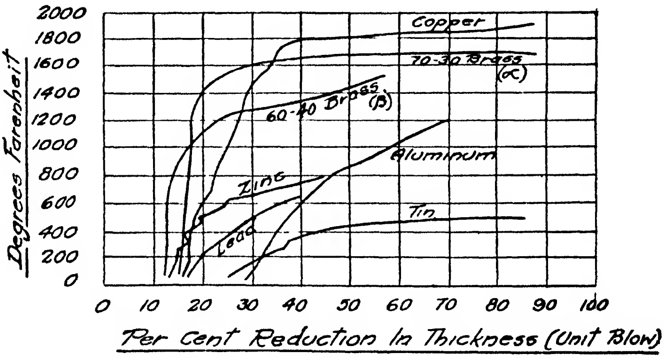


FIG. 239.—Forgeability of non-ferrous metals, measured by distortion under a unit load at varying temperatures. (*After Kent* [4])

slug cooled off. Heat contained in the slug is not likely to affect the results in this case to any great extent, as the slugs were too small to hold an appreciable amount of heat.

Fig. 240 shows a group of aluminum, " duralumin " and copper press forgings. It is said that in trimming " duralumin " forgings a pair of knife-edge cutters to pinch the scrap off are better than the usual punch and die method, as the flash is inclined to be quite brittle.

Brass for Forging.—Three phases of brass have been described: Alpha brass (under 36 per cent zinc), which has the face-centered cubic structure of copper. In fact, alpha brass is zinc dissolved in copper and occupying spaces in the copper lattice. This phase is cold-worked easily.

Beta brass, which has a body-centered cubic lattice, and consists of an alloy CuZn, in which some of the alpha phase is soluble (when the zinc content is between 36 and 45 per cent at 900° F.). This phase is best adapted to hot work.

[4] See footnote, p. 267.

Table XXII

COMPARISON OF THE HARDNESS OF COPPER AFTER HOT-WORKING, COLD-WORKING AND ANNEALING

(*W. L. Kent* [4])

Brinell Hardness Numbers			Forging Temperatures	
A Cold-Worked	B A-annealed	C Hot-Worked	Degrees C.	Degrees F. (approximately)
76 0	77-70 5	68 6	300	575
75 8	43 8	67 0	450	850
77 5	42 4	66 9	550	1025
79 0	43 9	58–46 7	600	1100
80 3	42 9	42 6	650	1200
81 3	42 9	44 6	700	1300
83 0	42 7	44 5	850	1550

A Cold-worked to same reduction as C
B Cold-worked samples annealed 10 minutes at 300° C.
C Hot-worked under 50-ft.-lb. blow

Gamma brass, Cu_2Zn_3, which begins to occur above 48 per cent zinc, is not easily worked either hot or cold.

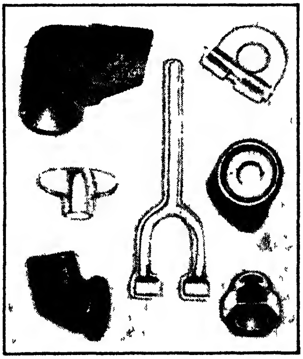


Fig. 240.—A group of aluminum, "duralumin" and copper press forgings.

Fig. 241 shows very clearly the relative plasticity and forging range of the brasses. Thus pure copper, at the right, is more plastic than the alpha brasses (central portion), but less plastic than beta brass (at the left). These data were prepared by Alan Morris[5] from drop-hammer tests in which slugs ½ in. in diameter and ¾ in. in height were heated to the various temperatures and then compressed under a uniform 200-ft.-lb. blow. The per cent reduction in height is taken as the measure of plasticity. These results may be compared with Figs. 239 and 133.

Referring to the constitution diagram for the copper-zinc alloys,

[5] Alan Morris, "Plasticity of Copper-Zinc Alloys at Elevated Temperatures," Technical Publication 390, A.I.M.M.E., Institute of Metals 125, 1931.

Fig. 13, it may be noted that only two or three points in the upper left corner of Fig. 241 represent pure beta brass. A brass containing, say, 61 per cent copper is all beta phase above 800° C. or 1472° F. Below that temperature the alpha phase begins to precipitate out, with cooling, until at 600° F. the alpha phase becomes decidedly predominant with accompanying reduced plasticity. A good illustration of this phase change and the attendant crystal structure has been presented by Mehl and Marzke.[6]

One important manufacturer of brass forgings specifies a mixture of 59 per cent copper, 39 per cent zinc and 2 per cent lead, to be forged at

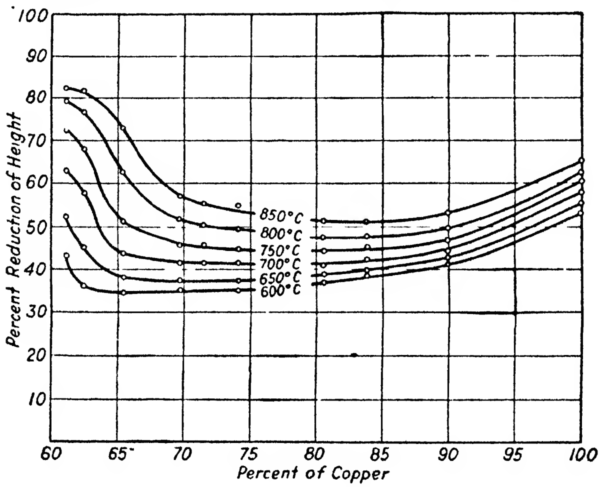


Fig. 241.—Plasticity of copper-zinc alloys at temperatures between approximately 1100° and 1550° F (*Morris* [5])

1400 to 1450° F. At this temperature the alloy is just on the edge of the all-beta area (Fig. 13). At lower temperatures it should contain a certain proportion of the alpha phase. Manufacturers who forge, for the sake of finish, at 1200 to 1250° F., and even lower, may properly specify 41 to 45 per cent zinc.

Another recognized authority gives the composition: 52 per cent copper, 48 per cent zinc, when the part is not to be machined; and 50 per cent copper, 48 per cent zinc and 2 per cent lead when it is to be machined. This mixture is beta brass very close to the border of the brittle gamma phase.

[5] See footnote, p. 269.

[6] R. F. Mehl and O. T. Marzke, "Studies upon the Widmanstätten Structure, II. The Beta Copper-Zinc Alloys and the Beta Copper-Aluminum Alloys," Technical Publication 392, A.I.M.M.E., Institute of Metals 127, 1931.

The presence of from 1 or 1½ per cent up to 3 per cent of lead in the mixture is common practice. It makes for easier machining and materially reduces the tendency to crack in the beta brasses. A certain amount of lead seems to be soluble in the beta crystals. An excess separates out along the grain boundaries and is a source of weakness.

In his experiments, Kent[4] investigated a 60 : 40 brass, with and without a 0.56 per cent lead content. He commented with reference both to cracking and to forgeability that it was quite evident that the alloy containing lead was the more satisfactory. He continued that "As in 70 : 30 brass, micro-examination showed that cracks in the lead brass followed the crystal boundaries, and chiefly the boundaries

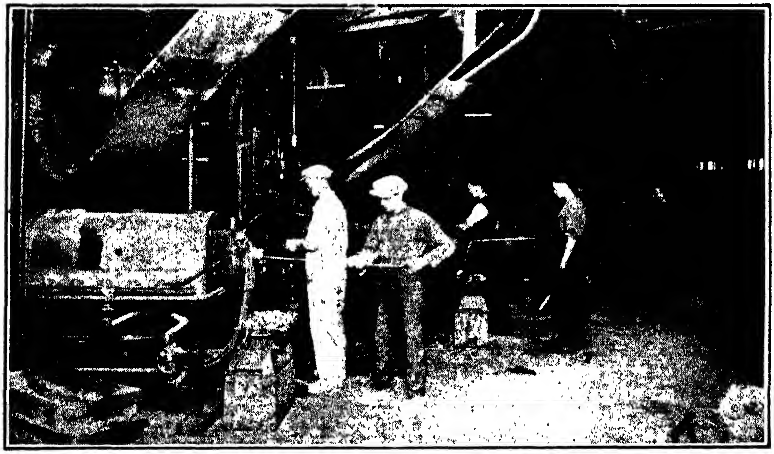


FIG. 242.—A group of forging presses producing 300 to 1100 pieces per hour each.

between alpha and beta grains, where lead was segregated. The absorption of alpha by beta became noticeable at 600° C. and complete at 750–800° C. The disappearance of surface cracking in lead brass may be accounted for by growth of the beta grains since lead was no longer concentrated at the grain boundaries."

One American manufacturer gives the usual mixtures for forging at 1250 to 1300° F. as containing 56 to 63 per cent copper, 0 to 3 per cent lead, 0 to 3 per cent iron, balance zinc. This would vary from beta brass to a solution containing some alpha. He comments that "mixtures containing 87 to 100 per cent copper which include aluminum bronzes and pure copper are also forged. With a copper content below 56 per cent the brass (gamma phase) is brittle. Those containing 63

[4] See footnote, p. 267.

to 86 per cent copper (alpha phase) are hard on dies causing them to crack and also develop hot shortness."

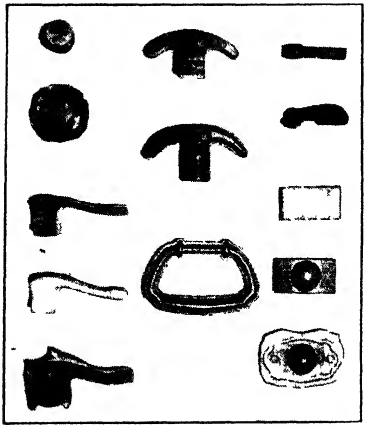


FIG. 243.—Press forgings produced from blanks sawed from extruded bars and, in two cases, preshaped cold.

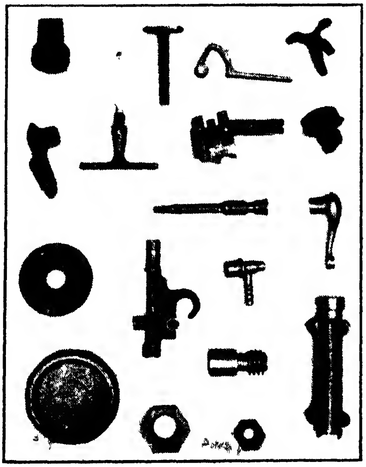


FIG. 244.—Power-press forgings, both American and European, held to tolerances between ± 0.005 and ± 0.010 in.

Brass Forging Practice.—Fig. 242 shows an installation of fast tie-rod frame forging presses in a well-equipped American brass forging plant. Extruded rod usually round in cross-section is sawed to length

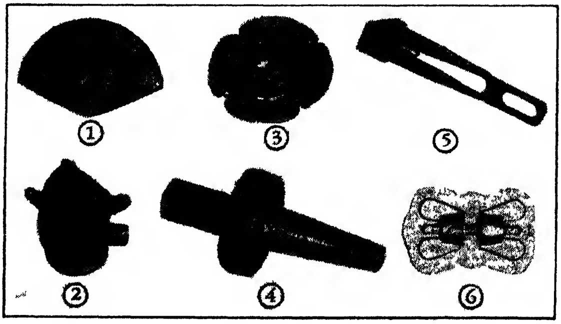


FIG. 245.—A group of brass press forgings, parts 3 and 6 being untrimmed.

in power hack saws automatically fed, or sheared to length in small presses with dies shaped to the bar. The shearing cut is made at a slight angle if a fairly square end is required.

As most small press forgings are completed in a single blow, there is considerable advantage, when the pieces are not symmetrical, in having a blank which reasonably conforms to the ultimate shape of the forging. Accordingly, as illustrated in Fig. 243, it is frequently desirable to use rod extruded to such a cross-section that, when sawed up into blanks, relatively little metal movement will be required to fill the die. The result of care in planning the blank is a reduction of scrap or flash loss as well as increased die life.

Note in Fig. 243 that two of the pieces were given three operations. That is, the blank cut from the extruded bar was struck once cold to further shape it to the forging. It is also possible to use dies to pierce and blank suitably shaped slugs, as for the loop handle in Fig. 243.

In some cases small, irregularly shaped parts can be ganged together to permit the use of a simple slug for the group. Thus brass elbow fittings which would otherwise be too small to hold the heat for forging can be made in a three- or four-cavity die from a plain rectangular slug with relatively little scrap loss.

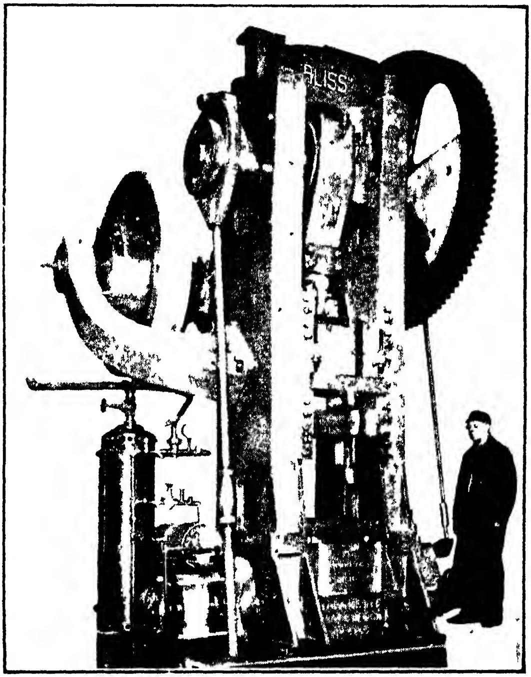


Fig. 246—A heavy forging press with hydro-pneumatic relief cushion built into the bed. (*Marquette Tool & Mfg. Co.*)

Returning to Fig. 242, the slugs are loaded into the back of semi-muffle, high-speed-type, gas-fired furnaces similar to the one in the foreground, or longer. A helper is usually provided to deliver the slugs to the press man and to keep the furnace loaded. The gas-fired furnace seems to be preferred over both oil and electrical types.

Fig. 244 shows a group of simple and intricate brass press forgings some of which are American made and some foreign. In general, the tolerances range between plus or minus 0.005 in. and 0.010 in. The

surface finish is clean and smooth with a slight discoloration which is easily removed by pickling in dilute nitric acid.

For figuring shrinkage allowances, the coefficient of expansion for brass is about 0.00000957 in. per inch per degree Fahrenheit. If the temperature of the forging in the die is assumed at 1450° and normal atmospheric temperature is taken at 70°, then the difference 1380°× 0.00000957 gives 0.0132 in. allowance per inch oversize in making the die.

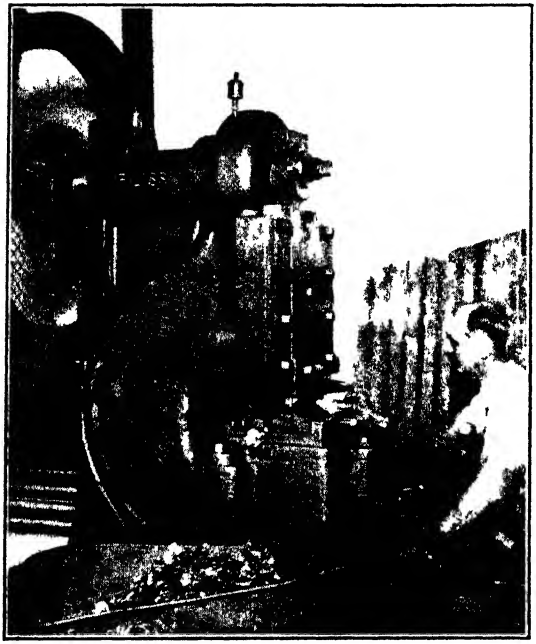


Fig. 247.—The trimming of brass forgings is generally done cold in small presses.

The clearance angle for knocking out, required in drop forging, can usually be omitted or greatly reduced. The presses are ordinarily fitted with a cam-actuated knockout, a direct-connected lift-out with trip release or a hydro-pneumatic knockout in the bed. Cross-bar or cam knockouts in the slide can be provided as required. In the case of weak-bottomed dome-shape parts, and the like, the forging temperature, clearance angle and knockout time must be controlled to prevent possible distortion of the forging.

In Fig. 245, part 4 was forged in a closed die in order to force the metal to fill both extremes. The other parts are forged with flash, which has not yet been removed in the case of parts 3 and 6. Flash has the advantage of acting as a means of relief for surplus metal. Where there is a possibility of overloading the press it may be built with a hydro-pneumatic overload relief in the bed as shown in Fig. 246. In this construction the high pressure is created and maintained entirely within the press-bed. The limit load is easily adjustable.

The flash around part 3 (Fig. 245) serves the double purpose of creating resistance to insure filling the extensions on both sides, and taking the force of the four knockout pins to lift the part out of the die. Flash

is frequently created to help force metal down into a deep cavity or corner of a die.

Part 6 is an example of two light pieces ganged together and forged out of a simple cylindrical slug. They are separated in the trimming operation.

As the average brass forging is fairly light in section and cools quickly, most of the trimming is done cold, as in Fig. 247. The end wheel and inclinable type presses are also used for hole-punching and slug-shearing operations.

CHAPTER XIII

PRESS CHARACTERISTICS AND MODIFICATIONS

A SIMPLE pendulum swinging freely comes easily to rest at each end of its swing. There it reverses its direction again, moves with smooth acceleration to a maximum velocity in the middle of its swing, and decelerates with equal smoothness to rest at the other extreme. That is harmonic motion, which might merit the title "the ideal mechanical movement."

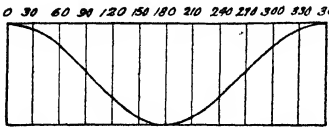


FIG. 248. — The harmonic crank motion, widely used by reason of its simplicity and smoothness. For velocity change see page 195.

The Crank Motion. — A slide moved back and forth by a rotating crankpin in proper relation, is also following the same smooth harmonic motion. Fig. 248 shows the conventional harmonic-motion curve for a crank-actuated reciprocating slide. The rotary motion of one cycle of the driving crankpin is plotted horizontally. The reciprocating motion or stroke of the slide is plotted vertically. This, of course, is practically the characteristic motion of the working slide or ram of the average punch press. It is modified slightly around midstroke by the angularity of the connection.

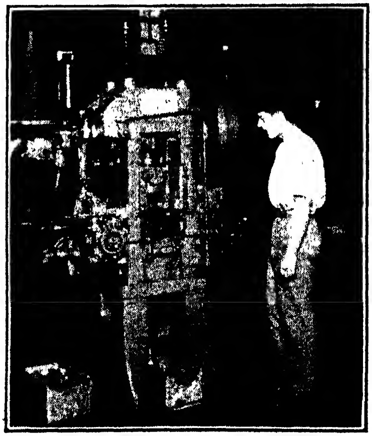


FIG. 249.—An eccentric-shaft high-production press employing a ¾-in. crank motion stroke at an operating speed of 450 SPM

The foregoing is simple and elementary but provides a starting point for a discussion of many modified and specialized types of press motions. The ease of the crank motion itself explains its very general use, even in our modern efforts at ever-increasing speeds. Thus Fig. 249 shows a little automatic press of about 15-ton capacity operating smoothly at 450 strokes per minute.

Contrast with this the rather awkward looking wiring press at the left in Fig. 250, which has a 16-in. stroke.

These two extremes and many other types of presses, most of them with numerous variations, employ the crank motion. Their differences and relative merits will be considered later in a discussion of press frames, driving means, etc. These numerous modifications of the crank-motion press are used in one way or another for almost every conceivable metal-working operation. Specialization and quantity production have, however, brought forth many special motions or groups of motions par-

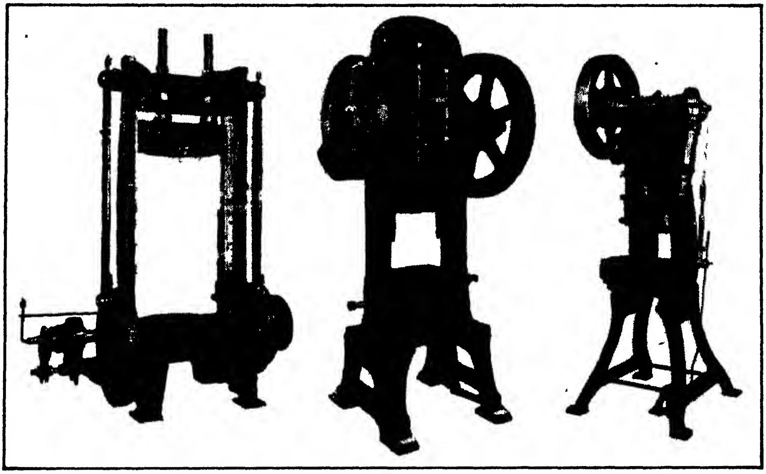


Fig. 250.—At the left, for comparison with Fig. 249 an outside drive wiring press with a 16-in. crank motion stroke at 25 SPM.

In the center a straight-sided press with cam-actuated movement and dwell for curing rubber. Note wedge adjustment in the bed.

At the right, an inclinable press with "beaver-tail" bottom stop mechanism for extended dwells in curing celluloid, rubber, fiber, cardboard, etc.

ticularly adapted to some specific class of work. Accordingly the first general step will be a study of press motions.

Cam Actions and Dwells.—One obvious alternative to the crank is the use of cams, whereby any desired motion may be obtained. Fig. 250, in the center, shows a typical cam action press built in a conventional frame to obtain a bottom dwell for curing a rubber or fiber product. Similar modifications of "C" frame or inclinable types, fairly long stroke machines, and wide presses have been made with equal facility. Cams also are largely used throughout the trade for the operation of knockouts and other auxiliary functions. In general, however, they are

avoided where possible as they are more cumbersome and slower than crank motions and are subject to higher unit bearing pressures under difficult lubricating conditions.

Bottom Stop Presses.—Another method of obtaining a bottom dwell, which is used in the curing of celluloid, fiber, cardboard and other products, is to arrange the clutch so that the press may be stopped at bottom center under full load, as well as at top center. This would normally put an excessive load on the clutch to avoid which a special Geneva action known as the beaver-tail stop[1] is interposed in the gearing as shown at the right in Fig. 250. This brings the driving gear itself to rest as the slide reaches bottom center and gives a dwell period during which the clutch may be disengaged without stress due to the press load. As a positive clutch is used on the back shaft, the stop mechanism is repeated at the top center stopping position so that the clutch has only the inertia of the back shaft to overcome (not that of the big gear) in starting. In such equipments several teeth of the big gear are cut away back of the beaver-tail cam and a pair of rolls mounted on the side of the back shaft pinion engage the cam and take up the drive through the period where the gear drive is interrupted. The equipment gives the fast smooth opening and closing action of the crank motion with a dwell which may be regulated to suit the product.

Shockless Extrusion.—Fig. 251 shows the motion curve of a type of collapsible tube extrusion press in which the same beaver-tail stop mechanism is used for an entirely different purpose. One of these presses illustrating the arrangement of the drive is shown at the left in Fig. 252. Here the function of the stop mechanism is to *remove the impact shock* from the tools. To accomplish this it brings the press slide to rest just as the tools reach the work and then accelerates it gradually to accomplish the extrusion.

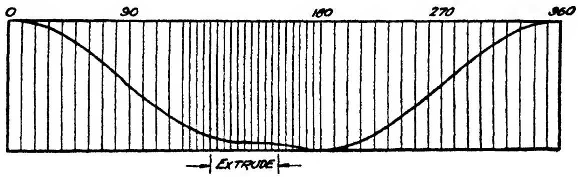


FIG. 251.—The Gabriel stop curve for extrusion, timed to come to rest as the punch meets the work and then accelerate easily for a uniform and gradual extruding action.

[1] Patented by Charles R. Gabriel; design reference: "Ingenious Mechanisms" by Franklin D. Jones, The Industrial Press, 1930, page 100, The Beaver Tail Stop Mechanism.

In Fig. 223 the working portion of this motion was compared with that of the crank motion and knuckle-joint motion, both of which are also used for extrusion presses. It may be noted in the figure that extrusion begins at a relatively high rate of flow in the knuckle-joint and then slows down rapidly, practically ceasing an appreciable time before the end of the cycle. In a crank press, extrusion begins even more suddenly and slows down even more quickly. The type of press shown in Fig. 252, however, is easily adjusted so that the stop point coincides with the easy contact of tools and metal. Extrusion begins with a mechanically powerful and easy acceleration and continues at a practically uni-

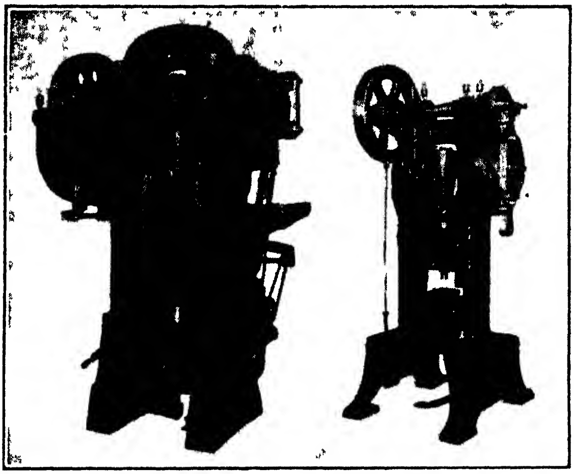


FIG. 252.—At the left, a shockless extrusion press using the "beaver-tail stop" to arrest the tools as they contact and then time the rate of extrusion. At the right, the shockless principle applied to punching steel. A straight-sided press with the "beaver-tail stop."

form rate which is materially lower than the initial rates in either of the other types of presses.

The elimination of impact shock shows up in operation in reduced tool breakage, with attendant savings in lost time for tool changes. The reduction in peak rate of extrusion results in a lower degree of heating and permits somewhat greater operating speeds.

Fig. 252 also shows an application of the same principles to heavy blanking work with apparently similar results. The possibility of carrying these principles into other specialized fields is of interest.

The Knuckle-Joint Motion.—Knuckle-joint presses, Fig. 253, sometimes confusingly referred to as toggle-joint presses, are popular and

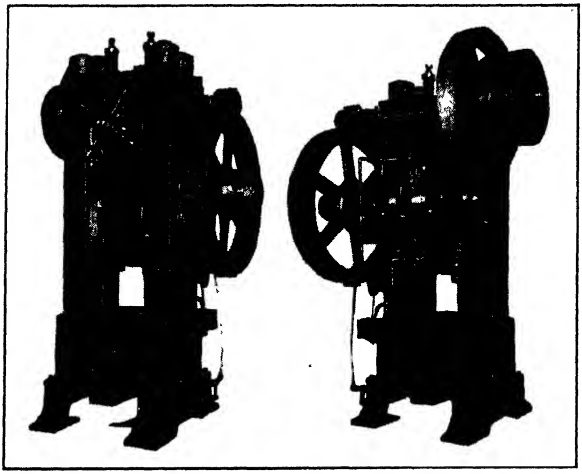


FIG. 253.—Front and back views of a knuckle-joint press. Note the massive frame, the knuckles in the bent position, the crankshaft at the back which actuates them.

economical for bottom stroke work requiring extremely high pressures. They employ a crank motion at the back of the press to alternately straighten out the knuckles, Fig. 254, thereby applying the working pressure, and then bending them again to lift the slide. The knuckles in the open position will carry comparatively little load, and, owing to their angle when open, the press strokes are comparatively short. As the knuckles are straightened out toward bottom center, the toggle action gives a higher and higher mechanical advantage to the driving

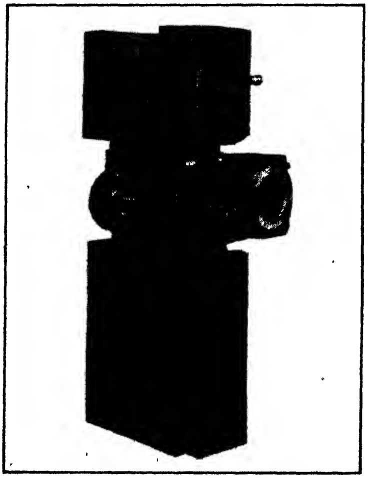


FIG. 254.—The links and connection of a knuckle-joint press in the straightened or loaded position.

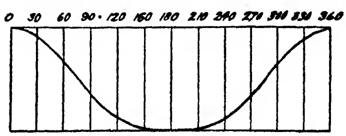


FIG. 255.—The knuckle-joint motion resembling the parent crank motion in ease but slowing down to a partial dwell at the bottom.

crank. The theoretical maximum pressure capacity approaches infinity as the links approach the straight line, but this maximum is limited in fact by the bearing load and press frame capacities.

The working motion of the knuckle-joint press, Fig. 255, resembles that of a crank, except that it is materially flattened out and eased off toward the bottom. Whether this semi-dwell at the bottom is of value in giving the metal under compression time to rearrange and stabilize itself in its new position seems open to question. But the high mechanical advantage gives this type of press a much higher load-carrying capacity, in proportion to its weight and size, than is found in other types. The working range is a very short distance at the end of the stroke, eliminating its use for most forming and blanking work. The usual field of the knuckle-joint press is coining, embossing, swaging,

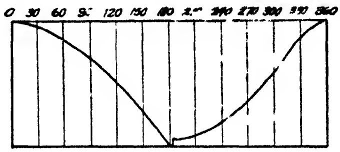


Fig. 256.—An approximate curve for the action of the power screw press or percussion press.

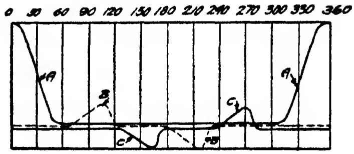


Fig. 257.—Motions of the Flat Edge Trimming Press. *A*, the main cam dwelling to maintain the cutting relation. *B* and *C*, the bed cam actions producing the four direction shearing movements.

sizing (sometimes hot sizing) and, when suitably arranged, extrusion. These operations were discussed in Chapters X and XI.

Percussion Presses.—For comparison with the motion curves of the knuckle-joint coining presses, Fig. 255, and eccentric-shaft forging presses which follow the crank motion, Fig. 248, there is presented in Fig. 256 an approximate curve for the action of the power screw press or percussion press. Here a flywheel attached to the upper end of a screw is friction driven with increasing velocity as the slide descends, until impact with the work absorbs the (whole) energy of the wheel. Except that it is much slower, this resembles the action of the drop hammer, where all energy of the falling ram must be absorbed by the work. After the rebound the flywheel of the screw press is backed up by a reverse friction drive to the starting point.

Flat-Edge Trimming Press.—Fig. 257 shows the interesting motion curve of the flat-edge trimmer, Fig. 65. Here three cam actions are combined. The first controls the press, bringing it down to close the

dies with their cutting edges in proper relation inside and outside of the drawn shell which is to be trimmed, Fig. 63. Then a vertical shaft at the back operates a ring gear in the table of the machine. This gear carries cam races which impart front and back, and right and left, trimming motions to the two slides built into the table. The principal moving parts in the table operate immersed in a bath of oil.

A series of distance pins around the upper die are ground flat with it and ride upon the surface of the lower die. Under the clamping pressure of the hold-down cam these maintain accurately the relation of the cutting edges to insure clean square shearing.

Cam Stripper Perforating Presses.—Fig. 258 illustrates a simple but peculiarly effective auxiliary cam motion widely used on presses for multiple perforating operations. The press slide, Fig. 259, carrying the perforating punches follows the harmonic, or crank-motion, curve. The stripper follows exactly the same curve to the point where it meets the metal which it clamps positively while the punches pierce and strip. In timing, it resembles a spring stripper, and in similar fashion it permits the shortest possible punches and the least possible motion relative to the punches. Its positive clamping of the stock also minimizes the bow or buckle which is the inevitable result of close multiple perforating operations. The die is shown in Fig. 39. The timing of the cams is obtained by turning the holding or dwell surface from the shaft centers and the moving surface from the crankpin centers. The corners, of course, must be eased off. The stripper slide is usually returned by spring action.

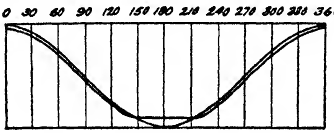


Fig. 258.—A cam-actuated stripper mechanism following the crank motion like a spring stripper but giving a positive holding action.

Fig. 259.—A fast-acting perforating press with positive cam stripper or hold down per Fig. 258.

Drawing Presses and Attachments.—In the performance of drawing operations, the terms single-, double- and triple-action refer to the use of one, two or three distinct working movements in the tools. Thus single-action drawing, Fig. 143, or redrawing, Fig. 148*D*, is done with a single-motion press without any mechanism or attachment for blank-

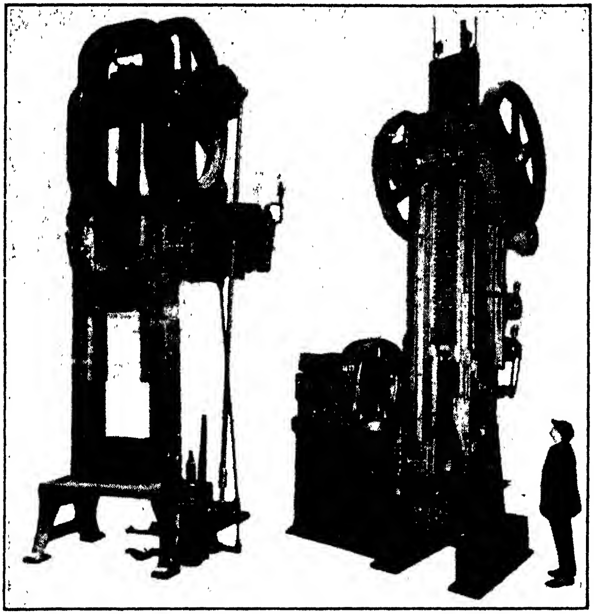


FIG. 260.—At the left, the "slow draw" drive which increases the production rate per minute without increasing the actual drawing speed.

At the right, a rack-and-pinion type reducing press with 9-ft. stroke and automatic reversing gear.

holding. This is necessarily limited to relatively thick metal or to small reductions in thin metal.

Double-action work is that in which a definite blank-holding action is required, Fig. 135, to hold the metal against the formation of wrinkles while another motion does the drawing. This requirement may be met by furnishing a double-action press for both holding and drawing, or a single-action press for drawing fitted with a suitable attachment for holding.

Triple-action equipment is furnished for holding, drawing, holding again and redrawing where the metal will stand two draws without

annealing. This is done either with double-action presses with auxiliary blank-holding apparatus or with triple-action presses.

Single-Action Drawing.—For single-action drawing in the heavy gauges and single-action reducing in the lighter gauges, the common presses are the straight-sided and gap frame types and the long stroke reducing presses. All these have the ordinary crank motion drive shown in Fig. 248. Often for relatively long strokes the presses are fitted with twin driving gears to divide the torsional load between the two sides and slabs of the shaft. Torsional stresses are especially high in drawing operations as the peak load frequently occurs shortly below midstroke.

A modification of the crank motion which has been receiving favorable comment is the use of the patented slow-draw drive, Fig. 260, for presses for drawing steel and for extremely light gauges. This mechanism, as shown in Fig. 261, gives a uniform and constant drawing ve-

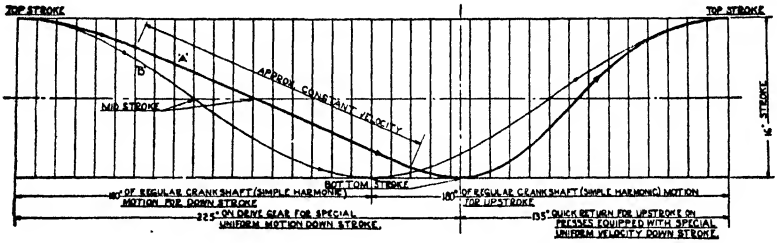


FIG. 261.—Compared at the same strokes per minute, the "slow draw" drive gives a slower and more uniform drawing speed and a quicker return than the normal crank motion.

locity and speeds up the return stroke so that a press may be run at a materially increased rate, in strokes per minute, without any increase to the drawing speed. The quick-return principle as a time saver resembles the action of shapers and planers in metal cutting. The advantage of limiting the drawing speed is particularly apparent in the drawing of steel where speeds in excess of 50 or 60 ft. per min. tend to cause welding of small particles on the steel die rings. The uniform drawing speed shows its worth especially in the elimination of chatter in the reduction of very light gauges and in broaching operations to which it is sometimes applied.

For extremely long strokes the rack-and-pinion type press, at the right in Fig. 260, has long been a standby. These machines require the reciprocation of a considerable mass and for that reason are limited as to speed. Their drives are arranged in many cases so that the return speed is faster than the down stroke as shown in Fig. 262. This may be

accomplished either electrically or by belt shifting on large and small pulleys. In either case, of course, the operating velocity is practically uniform. Control stops are so arranged on the side housings that the length of the press stroke and its limits may be adjusted to suit the job. Fast travel hydraulic presses with increased return speed and adjustable strokes are finding favor in this field.

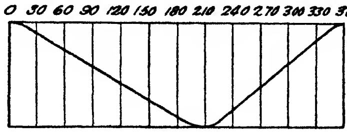


Fig. 262.—Rack-and-pinion presses have a uniform down stroke and quick return but rarely draw faster than 40 ft. per min.

Fig. 263 shows a type of crank-motion press developed for greater speeds in the long stroke reducing field. Here for a brass shell reducing and ironing job, for example, a crankpin velocity of 170 ft. per min. and an average velocity of 108 ft. per min. compare with a velocity of 16 to 36 ft. per min. for the rack-and-pinion presses. The motion is that of the crank shown in Fig. 248.

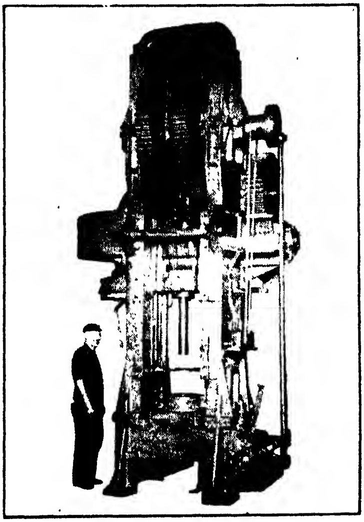


Fig. 263.—A new type reducing press permitting a 36-in. stroke at 18 SPM.

The ordinary crankshaft construction is used for reducing work for strokes up to three and occasionally four times the shaft diameter as on the press at the left in Fig. 260, but for strokes greater than that, the torsional strength of the shaft becomes relatively very low. Accordingly, for the longer strokes, the construction shown in Fig. 263 has been developed. Here the twin driving gears are mounted inside the press housings. The crankpin is pressed securely into them at a point near their circumference, and a double-driving pinion at the back insures a balanced drive free of torsional weaknesses.

One other interesting reducing method applied especially to ironing or wall reduction might be mentioned here. It is the Fulton Sylphon [2] progressive reduction process for long and extremely thin tubing in

[2] "The Manufacture of Thin-Wall Tubing," W. S. Lyhne, *Machinery*, p. 860, July, 1930.

which each draw is accomplished in a number of crank-motion strokes which are relatively short. A long frame press, Fig. 264, is mounted horizontally with a long hinged drawing punch attached to the crank-actuated slide. The die is mounted in an adjustable bed which is carried in gibs like the slide. An extension to the machine is fitted with a ratchet draw bench mechanism operated from the press slide and in unison with it. The shell or tubing, previously drawn as far as possible in other reducing presses, is started in this machine in such a manner that it will be pulled through the die by means of a tailpiece through a hole in its bottom, and at the same time pushed through the die by internal wall friction by the drawing punch. As the punch and the draw mechanism advance together, the tube is moved through the die. When

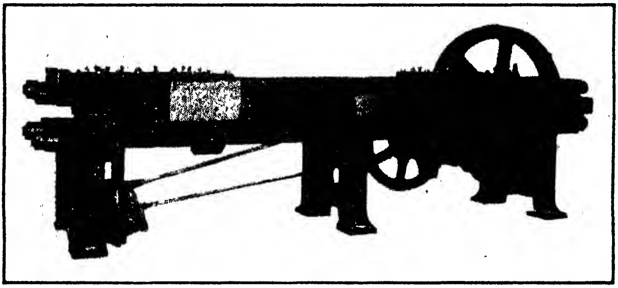


FIG. 264.—A horizontal progressive reduction press with 8-in. stroke, for thin-wall tubes up to 10 ft. long.

the punch moves back for the next stroke, the draw mechanism and tube dwell.

The machine has been applied especially to work in the non-ferrous metals (aluminum, copper, zinc and brass) and is reported to have produced remarkably uniform tubing up to 10 ft. in length with diameters of 1 to 9 in. and wall thicknesses down to 0.004 in. The reductions in wall thickness per operation are reported at 40 to 50 per cent at speeds of 80 to 320 in. per min. The higher speeds were used for the smaller tubes. Brass tubes produced from cast shells, with or without a preparatory machine finishing, were reduced satisfactorily, exhibiting excellent refinement of structure due to the working undergone.

Accessory Blank-Holding Attachments.—Many if not most drawing operations require that some means be provided for blank-holding, that is, keeping the metal flat on the die surface while it is being drawn. This blank-holder must be adjustable in such a manner that it will hold the metal rigidly, preventing the formation of wrinkles, and yet permit the metal to flow and rearrange itself with sufficient freedom so that it will

not tear along the side. The fact that the plastic working or rearrangement of the metal takes place almost entirely in the blank-holding area makes the holding means extremely important.

For a great deal of this work it is economical to use the ordinary single-action crank press equipping it with a suitable drawing attachment under the bed or bolster plate of the machine. The die is then the inverted double-action type as illustrated in Fig. 265. Here the die ring with suitable drawing radius, knockout, etc., is mounted on the press slide. The punch or male member is mounted on the bolster, and around it is the blank-holding "ring" riding on pins which go down through the bolster to the drawing attachment beneath it.

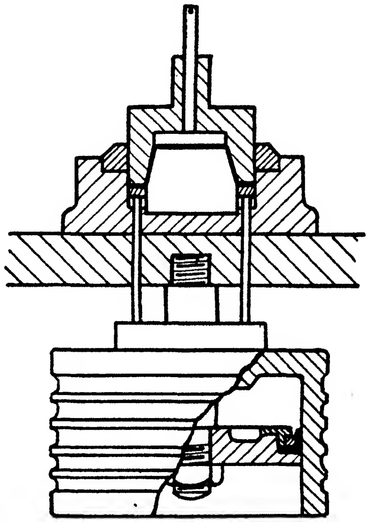


Fig. 265.—The inverted type drawing die for double-action operations in single-action presses.

There are a number of types of drawing attachments available, notably, rubber bumpers, springs, spring mechanical devices, air cushions and air-controlled hydraulic (hydro-pneumatic) cushions, of which the last two are the outstanding modern types.

Springs and rubber are the oldest and cheapest and for that reason are still used on quite a variety of work. Aside from the question of convenience, these are subject to criticism on the ground that the blank-holding pressure which they give rises as the draw progresses, whereas it is held that in making severe draws, as on relatively light gauge material, scrap loss due to breakage is much reduced by having a practically uniform pressure.

Certain it is that in rubber and spring attachments the pressure rises in practically direct proportion to the deflection. The rate at which it rises, however, is governed by the length of the springs or rubber compared to the drawing stroke. Thus if the attachment is sufficiently long the rise in blank-holding pressure from the beginning to the end of the draw may be held to reasonable limits.

Fig. 266 gives, for example, the results of a series of compression tests on new live rubber bumpers. The curve shows the rise of the blank-holding pressure in pounds per square inch of the original plan

area of the rubber, plotted against per cent compression or reduction in length. Re-application of the load indicated that the rubber had taken some permanent set from the first test. Age, temperature and mixture also have considerable effect. A very general rule was drawn, however, that the rubber will exert a holding pressure of between 6 and 9 lbs. per sq. in. of cross-section area, per 1 per cent of compression. In practice the compression should never exceed 20 or 25 per cent. During the tests it was noted that the rubber settled a little at each loading, losing as much as 5 per cent of its pressure on standing a couple of minutes. After a 20 per cent compression the rubber had a set at no load of 1 to 2 per cent and after 50 per cent compression a set of 10 per cent some of which was retained to the next day. Heat generated in the course of a day's operation may alter the rubber pressure sufficiently to require several readjustments.

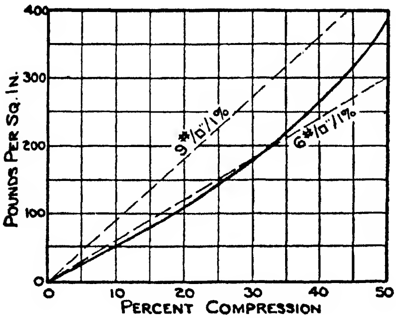


Fig. 266.—The highest and lowest curves (solid lines) from a group of rubber compression tests.

Fig. 166, page 185, shows a typical spring drawing attachment on a large press fitted with dies for metal casket work. The springs are arranged in nests as shown and are adjusted by taking up on the nuts at the top of the long suspension rods. The pressure plate at the top of the springs may rest against limit screws through the bed or directly against the under side of the bolster plate. The blank-holding ring rides upon pins through the die shoe, which in turn rest upon pins through the bolster to the pressure plate. Relatively small-diameter car springs of heavy square wire are used on such attachments and are selected on a basis of about 18 in. of spring length per inch of draw.

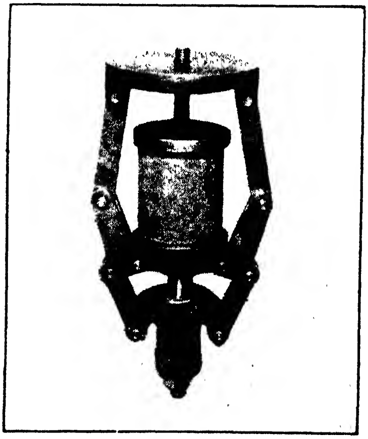


Fig. 267.—A rubber drawing attachment with toggle links designed to keep a nearly uniform pressure.

It is reported that the particular installation shown in Fig. 166 has

since been changed over to the use of air cushions for greater convenience and ease of adjustment.

Several drawing attachments have come out from time to time employing various linkages designed to equalize or compensate for the rising pressure of the energizing rubber or springs and therefore deliver constant pressure to the blank-holding ring. Such a device is illustrated in Fig. 267. Here a clever toggle linkage controls the blank-holding pressure so that it is absolutely constant throughout the draw. This holds, however, for a certain predetermined pressure only. When it becomes necessary to adjust this, there results an increasing or decreasing pressure varying with the amount of adjustment.

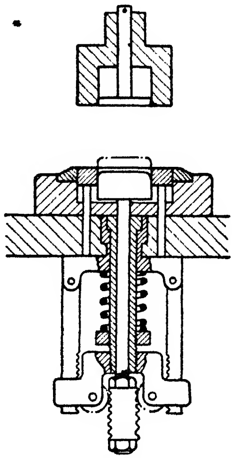


Fig. 268.—The Rhoades simplex attachment drives the punch upward by means of a reversing gearing approximately as shown.

An outgrowth of developments of this type is shown in Fig. 268. Here a reversing action is obtained through differential gearing or levers so that the punch, instead of being fixed to the die base, moves up as the blank-holding ring about it is forced down by the press slide. This permits drawing almost to the full amount of the press stroke, Fig. 269, although the relative drawing speed in the tools as they pass is equal to or exceeds that in the common arrangement of single-action presses with drawing attachments.

The blank-holding pressure is the direct resultant of the resistance met by the drawing punch. That is, the pressure is transmitted back through the gearing so that it varies with the thickness of the metal being drawn. The relative punch position can be adjusted, but not the blank-holding pressure. This always remains equal to the whole drawing pressure, whereas it is common practice, with other methods of blank-holding, to range from zero on heavy gauge material to between a fifth and half the drawing pressure on light gauge deep draws and as high as double the drawing pressure on shallow stretching operations.

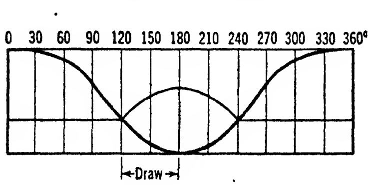


Fig. 269.—The crank motion of the slide (draw ring) is reversed for the punch (*see* Fig. 268).

A short heavy spring is provided to strip the shell and return the

device to its normal position. It is said to play only a minor part in the blank-holding action, however.

Figs. 265, 270 and 271 show the latest and most satisfactory of the drawing attachments, the air cushion and the cushion bed. The former illustrates the manner in which the blank-holding ring rests upon pins around the drawing punch. The pins are continued down through the bed to one or a group of air-pressure pistons or cushions under the bed. These cushions are connected to a suitable surge tank mounted near the press. The tank is connected to the shop air line through a regulator

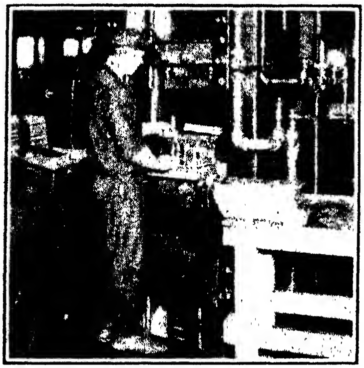


FIG. 270.—Press with air cushion attachment for drawing a rectangular shell. Note convenient pressure dial and regulator valve. (*Courtesy Marquette Tool & Mfg. Co.*)

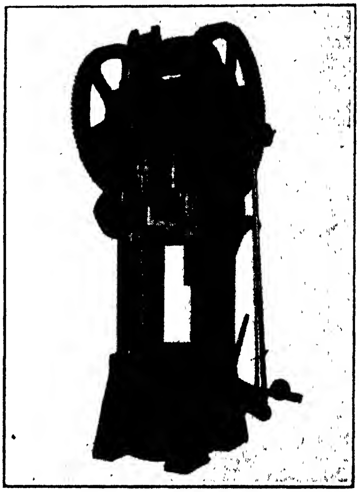


FIG. 271.—The built-in cushion bed on a long stroke single-action press for varied draw jobs.

valve and gauge conveniently located beside the press. The pressure applied by the cushion is resilient to allow for thickening of the material and is practically uniform during the drawing stroke.

In setting a new job the operator adjusts the blank-holding pressure by means of the regulator valve to the point at which wrinkles are held out without tearing. The adjustment is easily made, and once recorded it may be duplicated at will on subsequent set-ups. The time saving which this entails and the fineness of adjustment are outstanding features of this equipment.

Another development in this line is the cushion bed press in which the cushions and surge tanks are built right into the bed of the machine.

One of these units is shown in Fig. 271, a long stroke single crank drawing press. This arrangement makes for greater mobility in those shops which shift equipment frequently to suit changing manufacturing groups or methods.

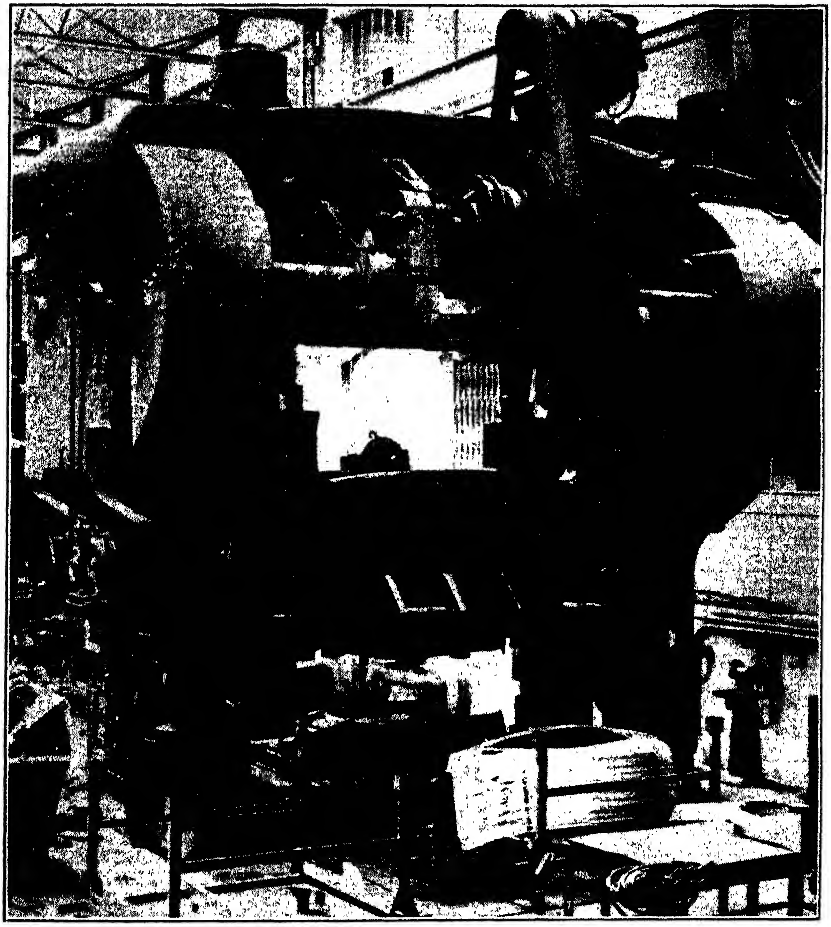


FIG. 272.—A large four-point single-action press with air cushions and locking device in the bed, in use in an automobile body stamping plant.

The principal object, of course, in purchasing a single-action press with drawing cushions built into the bed is to obtain maximum flexibility of equipment. Most of the large general-purpose presses and increasing numbers of the smaller ones are now so built. Such units are adaptable to drawing operations; to forming work where a pressure pad is required;

to combinations of blanking and drawing, or of blanking and piercing; or to plain blanking operations in which a pad is placed in the die and the pressure holds the sheet flat for accuracy and returns the blank to the surface for removal. Many of the smaller units are arranged so that the cushions or parts of them are removable for push-through blanking.

Fig. 272 shows a rear view of a "four-point" single-action press with air cushions built into the bed. The use of four cranks, to apply pressure at the four corners of large area slides, insures against tilting of the slide under conditions of unbalanced loading. The gear trains, which are completely encased to run in oil, are also planned so that unbalanced loading will cause a minimum of torsional misalignment. The small chain drive at the left operates two drums on which are adjustable cams to operate air values which control a hydraulic locking device attached to the air-cushions and the pressure pads in the bed or base of the press (which is well below the floor line). The function of the locking device is to delay the return of the cushions so that stampings which are drawn with a flange will not be damaged on the up stroke between the opposing pressures of a blank-holding ring and a knockout pad. For similar reasons locking devices are even more frequently required on double- or triple-action presses equipped with air cushions.

Cam Drawing Presses.—When single-action presses are equipped with blank-holding attachments under the bed, the relative action of the two functions (drawing and blank-holding) may be represented as shown in Fig. 273. The draw ring must follow the harmonic motion of the press slide. The draw plug (Fig. 265) is fixed upon the press bolster. The blank-holding ring, carried on the drawing attachment, dwells at rest until the draw ring contacts with it on the down stroke. It then moves down to bottom center and up again to its rest position following the motion of the slide. That is, it dwells through the idle portion of the press stroke and moves under pressure through the working period.

Compared with this, the blank-holding slides of double-action presses, in general, dwell under pressure during the drawing period and move out of the way under no load during the idling period. This is shown, for example, in Fig. 274.

Work is the product of pressure and the distance through which it is applied. The work done in drawing is the same for both single- and double-action presses. The work done in blank-holding on a double-action press is a negligible item, for while the holding pressure may be high, it is applied only through a working stroke represented by a very slight deflection of the working parts. But, taking a spring drawing attachment as an example, the slide of a single-action press must do work, compressing the springs, throughout the drawing stroke. A por-

tion of this energy may be returned to the system on the up stroke but the amount is limited, owing principally to inertia of parts. Therefore, especially on deep drawing operations the power requirement is less for a double-action press than for a single-action press with drawing attachment.

Like any highly specialized equipment the double-action press is designed throughout for a specific purpose and is not often used for other classes of work. Extended frames, high flywheel capacities, gearing adapted to midstroke loads, extra capacity in clutch and motor, and other features are pointed toward greatest utility for double-action

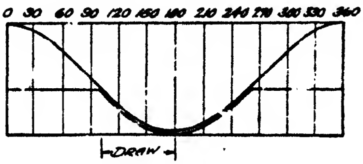


FIG. 273.—Relative movements of slide and drawing attachment on a single-action press.

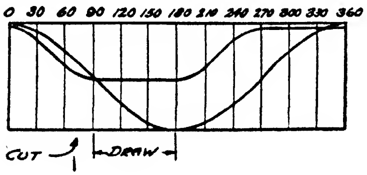


FIG. 274.—Movements of the crank-actuated drawing slide and cam-controlled cutting and holding slide of cam presses similar to Fig. 275.

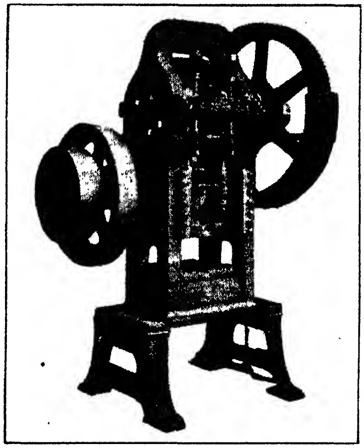


FIG. 275.—A cam drawing press of the type employing two-way cams to actuate the outer slide.

drawing operations. In this classification may now be included the new cushion bed drawing presses mentioned previously, which are planned specifically for drawing operations and offer certain advantages in convenience and flexibility.

Cam Drawing Presses.—Fig. 274 shows the typical action of the blank-holding and drawing slides of cam drawing presses such as the one shown in Fig. 275. The stroke is a little more than twice the maximum depth of draw to permit easy removal of the finished shell. When desirable, work can be pushed right through the bed of the press, which is a distinctive feature of double-action presses. Push-through drawing operations are faster and more positive as a rule than operations in which a shell must be lifted out of a die or stripped off from a punch.

Obviously only straight-walled shells with plain bottoms can be pushed through a die. But in the numerous cases where this is possible, the operating efficiency is high as one blank or shell may follow another without any lost time for disposing of the last one. For that reason this method is frequently used for automatic and semi-automatic operations. Thus one manufacturer keeps a large toggle press running continuously. The operator feeds 20-in.-diameter blanks down an inclined roller table to a nest on the die. The shells, over 10 in. in diameter and $\frac{1}{8}$ in. thick, are drawn right through the die and slide out under a bridge

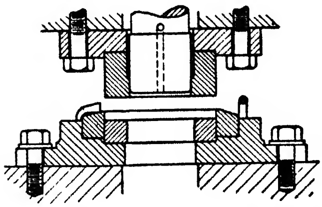


FIG. 276.—A combination blanking and drawing die for push-through work.

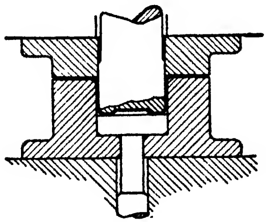


FIG. 278.—A double-action press die for work with a flange or a bottom forming operation.

FIG. 277.—An inclinable cam drawing press using two cams for holding down and a third at the side for lifting.

bolster onto a conveyor which carries them through a continuous annealing furnace and to the next operation without intermediate handling.

Fig. 276 illustrates a typical combination blanking and drawing die for push-through work in a double-action press. It may be noted that this die has a maintenance advantage over the type of combination dies shown in Figs. 265 and 268 which are used with underneath drawing attachments. This is the use of separate rings for the inner cutting edge and the drawing edge. When the die is inverted and these functions have to be combined in the same ring, the drawing edge must be redressed every time the cutting edge is reground.

Fig. 277 shows a C-frame press arranged with a die similar to that

shown in Fig. 276. By pulling the stock through from the coil and against the stop on the die, the operator is able to maintain a uniformly high production rate, catching every stroke of the press. Similar presses are also fitted with automatic double-roll feeds for coil stock and with friction dial feeds for secondary operations. In such cases spring latch fingers are often furnished under the draw ring to insure absolutely positive stripping of the shell. Such an arrangement was shown in Figs. 159 and 160. Stripping fingers are rarely necessary in hand feeding, however, as the punch may be vented to break the suction and the strained metal in the shell wall tends to expand slightly and stick in the die ring rather than on the punch.

Fig. 278 shows a typical double-action press die for work which cannot be pushed through. This includes shells which require some stamping operation on the bottom or those drawn with flanges or with tapered or shaped walls. A combination of piercing operations in the bottom with drawing is rarely attempted on double-action presses both because the punch slide on such presses is usually allowed to float to a certain extent to compensate for non-uniform metal thickness and because the logical arrangement would usually involve pushing the slug up into the punch instead of down through the die.

Work which cannot be pushed through the die must obviously be lifted out. For this several mechanisms are in common use. C-frame and inclinable machines of the type shown in Fig. 277 employ a lever under the bed actuated from the back of the blank-holder slide or, more commonly, from the return cam lever at the side of the press. Straight-sided presses usually use a crossbar under the press bed, suspended from the blank-holder slide by rods set back into the side housings. Both mechanisms are adjustable and both hold the knockout pad up to the top of the die until the press is tripped for the next stroke. This will occasionally interfere with locating the work for redrawing operations. In such cases a trigger lock mechanism is provided to permit the pad to drop back as soon as the last shell has been lifted free from the die. Air cushions with a timed valve control are also coming into use as knock-outs, especially on some of the larger double-action presses.

Figs. 275 and 277 illustrate two cam arrangements still in use at the present time. The difference is essentially in the method of returning the blank-holding slide. Some of the earliest double-action presses built in this country were underneath drive machines which employed cams to push up and hold the outer slide and depended upon the force of gravity to return. In later machines the driving mechanism was more conveniently arranged above the work and the cams held the outer slide down. Three ways of returning this slide to the up position then in-

cluded: springs, which have fallen into disuse; the separate return cam at the side, as in Fig. 277, which actuates a cross shaft and lifting yoke at the back of the press; and the two-way cams, Figs. 274 and 275, which both lift and lower the outer slide for blank-holding. The timing of the movement of the outer slide is a little more flexible and easier with the separate return cam, but the mechanical construction is somewhat better balanced with the two-way cam so that for practical purposes there is little to choose between the two constructions.

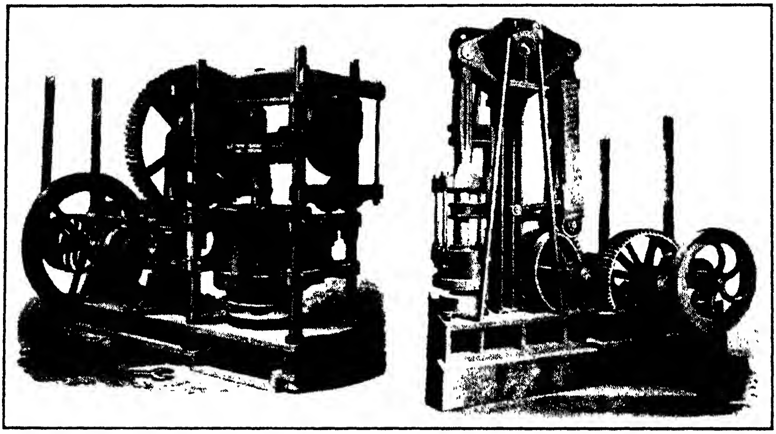


FIG. 279.—At the left, the No. 4 drawing press of 1881, many structural features of which have long been abandoned. At the right a walking beam drawing press of about 1880, weighed 31,000 lb., ran 9 SPM.

Before leaving the cam drawing presses it may be of interest to note something of their history. Their origin is said to date from 1859 in this country and possibly a little earlier in France. The Bliss and Williams catalogue for 1873 and the Stiles and Parker catalogue for 1874 both show double-action cam presses. By 1880 there were half a dozen different sizes and types. Shortly thereafter the underneath drive types with pull-down punch slide and cam-lifted blank-holder began to disappear. The positive cam return was just coming out as an improvement upon the use of springs or gravity to return the outer slide. The designs included some rather weird arrangements and other types which were clearly predecessors of our modern machines. The toggle presses did not appear for another decade.

Fig 279, copied from woodcuts in an 1881 catalogue, shows designs which seem odd in the light of modern practice. Note the thin spokes in the gears and wheels, the shrouded pinion and the mounting of the

gearing as a separate unit at the side. The press at the left weighed about 15,000 lb. and was quoted to run at 9 strokes per minute on dish pans, bird cage bottoms, milk pans, etc., up to 5 or 6 in. deep. The open rod frame construction has frequently tempted designers in the press trade but has rarely survived for any length of time. The columns, in this case wrought iron, 3½ in. in diameter, invariably sway and stretch unevenly owing to unbalanced strains which cannot be avoided in press work. Using the columns for bearings for the blank-holder causes maintenance troubles due to wearing shoulders at various levels as adjustments are made.

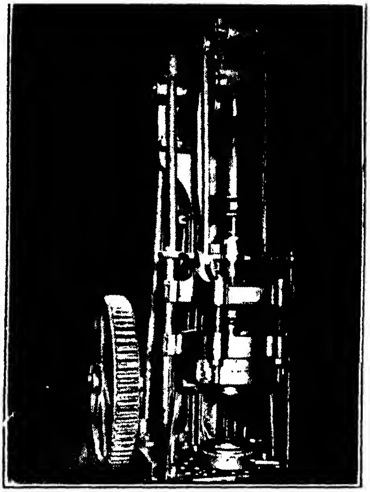


Fig. 280.—A machine identical with that shown at the right in Fig. 279, which survived half a century of operation.

Another odd design of 1878 or earlier is shown at the right, and in Fig. 280. A somewhat similar machine which is still in operation is shown on page 150. In this case the gearing and cams are mounted on an extension at the back of the press. Vertical links transmit the double-action motions up to walking beams, at the top of cast housings, and thence down again to the press slides.

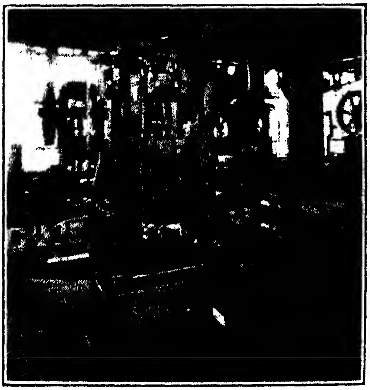


Fig. 281.—A high-speed double-action crank press for blanking and cupping first operation cartridge shells, 7 per stroke. Smaller sizes are used for cutting and cupping button covers.

Fig. 281 shows a modern double-action crank press, sometimes referred to as a three-crank press. It represents a type developed in the early days of double action work (prior to 1873). The 1881 catalogue shows a cut of a small double-action crank press and remarks that the design has subsequently been improved by the substitution of cams for cranks to improve the dwell. That judgment was premature, however, as the crank action types persist because of decided inherent advantages for certain classes of work.

Fig. 282 shows the timing curves for this type of press. It is a combination of two harmonic motions, one of which has a much shorter stroke than the other. The shorter motion is that of outer slide which

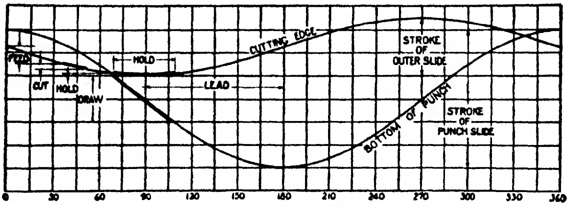


Fig. 282.—Timing relations between the cutting and holding slide and the (inner) drawing slide of a double-action crank press.

cuts the blank and partially holds while the inner slide draws the shell and pushes it on through the die. The outer slide is timed 60 to 90° ahead of the drawing slide, so that the near dwell of the former across

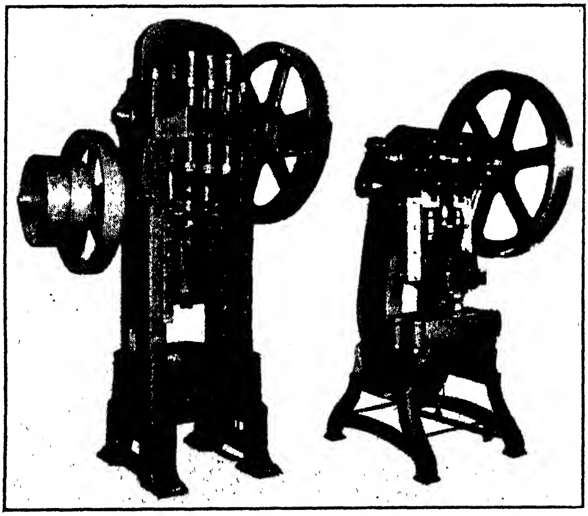


Fig. 283.—At the left, the use of two-way cams to operate both the inner and outer slides of a double-action press permits both to dwell with considerable latitude in timing.

At the right the inside slide holds the blank while the crank-actuated outer slide cuts, draws, bends, rivets, stamps, etc., or to suit.

bottom center coincides with the greatest (drawing) speed of the latter.

These presses are used, therefore, for blanking in combination with shallow draws in relatively light material such as button collets, cuff

and collar button parts, and the like; and with deeper draws in relatively heavy gauges as in the production of shell and bullet cups. Both classes of work require only a brief or negligible blank-holding action.

The advantage of these machines is that a crank motion requires less maintenance attention than a cam action and can be run very much faster. Therefore where a double-action press with a slight dwell is satisfactory and the production is large, such presses are the best obtainable. The press shown in Fig. 281 was built and arranged for blanking and drawing 7 first operation bullet cups per stroke and was one of many in wartime service.

A reversal of three crank principles is found at the left in Fig. 283. Here three two-way cams are arranged to operate the inner and outer slides of a special double-action press to obtain any desired timing. Thus in this case the outer slide may close a die or mould, and hold it. The inner slide may then descend to force some plastic material into the closed mould and then dwell to hold it under pressure during a brief curing period before both slides open.

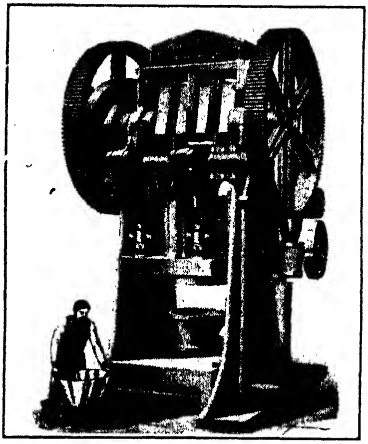


Fig. 284.—The connecting link between the cam and toggle presses, a machine of about 1890, in which both mechanisms were combined to obtain the blank-holding action.

Fig. 283, at the right, shows a double-action cam press in which the normal slide functions are reversed. Here the outer slide has the crank motion and the inner slide is cam-actuated so that it can dwell during the working period. In this particular instance the press is used for "weighing" rubber or squeezing it to a desired thickness with the inner slide and then shearing it to shape with outer slide.

It may be noted that all types of double-action cam and crank presses are built with both C-frames and straight-sided frames. The majority of smaller presses are of the former type, however, and are usually inclinable. The larger presses are usually made with straight-sided frames of the built-up, shrunk tie-rod type.

Fig. 284 shows an interesting link between the double-action cam and toggle presses which might be termed a cam-actuated toggle drawing press. The original illustration appeared in an 1890 catalogue. The inner slide for drawing purposes is crank-actuated as usual. The outer

or blank-holding slide is driven from a cam race inside the left-hand gear through a set of toggle links and levers. The rock shafts at the front and back are geared together by a pair of segments at the right. A heavy counterweight suspended below the segments helps to balance the weight of the outer slide.

The press is described as "much heavier and stronger in all its parts than any press hitherto put on the market." It weighed about 130,000 lb. and was priced under 8½ cents a pound. The frame is interesting as a predecessor of the bolted construction which enjoyed some vogue in the early part of this century. The full-length housings were tied together by a bed plate and crown bolted between them. The principal weakness lay in the fact that the three shaft bearings were difficult to maintain in alignment. One of them was carried in each housing and the third in the crown so that any weave or distortion could throw them out of line. This may be compared with modern construction in which all shaft bearings are bored in a single crown casting so that their alignment cannot be destroyed.

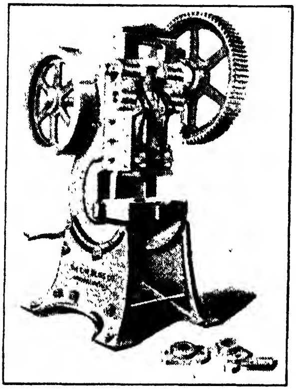


Fig. 285.—An inclinable toggle drawing press from a woodcut in an 1890 catalogue.

Toggle Drawing Presses.—The evolution of the toggle mechanism as a means of actuating the blank-holding slide of a drawing press took place between 1887 and 1890. Refinements in design and details of construction continue to be made; but the simple principles developed then were so fundamentally sound that they have changed very little in the intervening time.

Fig. 285 shows one of the early toggle drawing press designs. The outer slide was operated by two instead of four toggle links. A rock shaft at the back of the frame above the back shaft carried the levers which furnished the intermediate toggle action and which were in turn driven from the main crank of the press by means of a bearing at the back of the connection strap. This appears to have been quite an efficient design, as the toggle series included the conventional three dead centers. The dwell and probably the timing relation should have resembled closely that of more recent presses, as in Fig. 151.

These machines were built in both geared and non-geared types though the latter were undoubtedly used only for very shallow draws on account of the relatively small amount of flywheel energy available. Four bolts were provided between the outside slide and the blank-holding punch plate to permit independent corner ádjustment.

Fig. 286 shows a No. 15 toggle drawing press built in 1890. With the original built-in steam engine drive it weighed about 125,000 lb. and cost $10,000.00. Thirty years of its operating history have been reported with no major repairs or changes except substitution of an electric motor for the steam engine.

Almost every detail of the press has been modified and improved in modern practice, yet the underlying principles, like those of the automobile, remain unchanged. The most obvious improvement is in the arrangement of the gearing, which is now high at the back of the press. Brakes, clutches and bearings have also been much improved. The

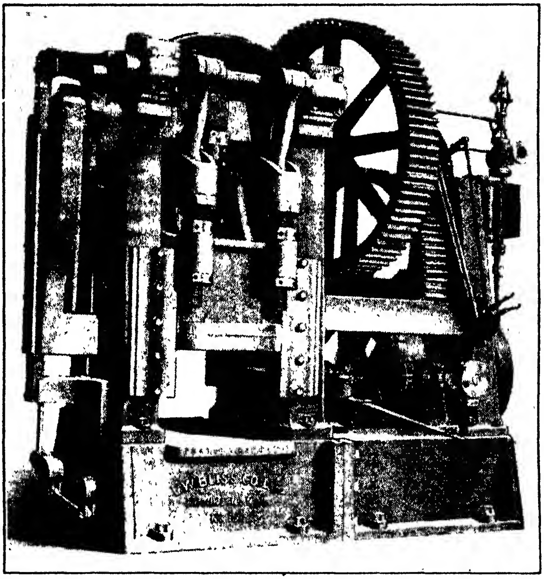


FIG. 286.—A toggle drawing press built in 1890 and used for thirty years or more in the production of wheelbarrow trays and road scrapers.

outside "banjo" slide, which actuates and counterbalances the blank-holding slide, has been moved in against the frame. In a still earlier design, especially of smaller sizes, this outside slide was driven by means of a sliding block on the outside crankpin and a cross slideway in the banjo slide, instead of the long connecting link now used.

A modification to the standard design, which appeared in 1901, involved the provision of means for adjustment in the length of the connection between the end of the crankshaft and the banjo slide at the side. This adjustment made it possible to cause the toggle links to pass their dead-center positions to a greater or less degree. Then instead of a practically smooth dwell there might be inserted a rise or relief

point in the midst of the dwell to permit the metal to flow or thicken up. This would appear to have been of small practical value for it did not survive.

Double-crank toggle presses lagged behind the single-crank type in development, as there seemed to be no great need for them until stamping methods began to be applied to the large area body work of the automobile trade. The early models, around 1909, were merely the single-crank type, shown in Fig. 178, widened out. The greatest milestone in this type came about three years later when the twin drive, for shaft and blank-holding mechanism, was introduced to divide the torsional load on these parts. This resulted in the development of such presses as that shown in Fig. 169, and many which are larger. The twin-drive principles have now been applied also to many of the larger single-crank toggle presses, as in Fig. 151, especially where they are used on relatively heavy gauge work.

Toggle Motions and Dwells.—Fig. 287 represents the timing relation for most toggle drawing presses. The inner or drawing slide has the regular crank motion. The shaft is usually stopped at about 15° back of top center, as that is the highest common point of the two motions. The toggle drive is timed about 30° ahead of the crank motion so that the blank-holding dwell begins at midstroke down and continues a little beyond bottom center.

Figs. 288 and 289 are arranged to show the development of the toggle motion dwell. Essentially this is a combination of driving parts arranged to multiply and extend the period of hesitation at dead center. A dead center is an instantaneous position of mechanical parts at which a driving member (crank, lever or slide) is traveling at right angles to the direction of travel of some other member which it is driving (usually through a connecting link). At that instant the velocity of the driven member should be zero, whatever that of the driver may be.

A toggle mechanism may be described as a grouping of cranks, levers and slides with the necessary connecting links, so that the train of movements may contain several dead-center positions at approximately the same time. If the motion is so controlled that the several points pass through dead center a little way and back through it again in returning, the effective dwell period may be extended within certain limits.

In Fig. 288 are a series of curves which illustrate respectively the effects of one, two, three and four dead-center positions arranged in unison. The original motion in each case is the crank motion, and one revolution of the crank is the cycle plotted. The letters at the left refer to the diagrammatic sketches of the typical motions shown in Fig. 289. In that illustration the sketches at the left show the up position of the

slides at the beginning of the cycles. The sketches at the right show the down stroke dwell position (at 180°). In each case the figures 1, 2, 3 and 4 indicate the dead-center positions which contribute to the dwell obtained.

Curve *A* and sketch *A* illustrate the result of driving a slide with a simple rotary crank motion, the starting point in every case. Note that

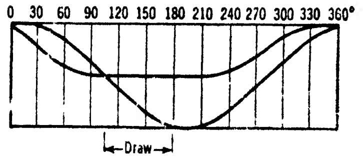


FIG. 287.—Timing relations between the drawing and blank-holding slides of toggle drawing presses.

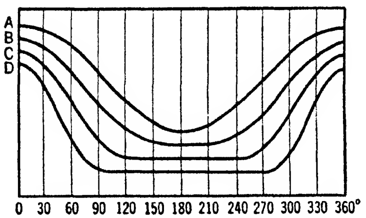


FIG. 288.—The development of the toggle dwell showing the effect of 1, 2, 3 and 4 toggle points or dead centers. Letters refer to linkages in Fig. 289.

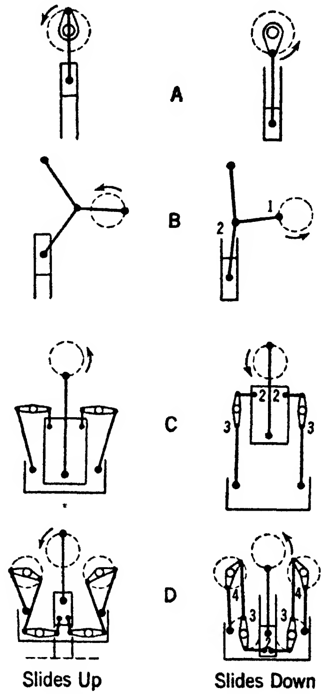


FIG. 289.—The crank motion, the knuckle-joint press, the standard toggle dwell and the four-point dwell producing respectively the 1-, 2-, 3- and 4-point toggle actions shown in Fig. 288.

as the crankpin, traveling at constant velocity, passes through its dead-center positions (1), the resultant velocity of the slide is zero, though there is no appreciable dwell period.

At *B* are illustrated the knuckle-joint coining press motion and linkage to show the effect of combining two dead-center positions. As the driving crank reaches its dead center (1) it straightens out the main

links to a second dead center (2). As increased mechanical advantage is the only object in these presses and no dwell is required by the work, the links are actually stopped a little short of the dead-center position to save time in the cycle. A short dwell might, of course, be obtained by extending the horizontal link or the stroke slightly so that the vertical links would pass slightly over their dead-center position and return.

At *C* is illustrated the most commonly used mechanism for driving the blank-holding slides of toggle drawing presses. Variations upon this linkage may be and have been made without altering the essential principles or results. It is a sequence of three toggle or dead-center points. The first is the top center position of a crank-motion pin (1) which drives a vertically moving counterbalance slide. This slide in turn actuates the rock shaft levers through short links which slightly overpass a dead-center position at the points 2. The rock shafts in turn slightly overpass a dead-center position at 3 as they drive the long links to lift and lower the blank-holding slide.

At *D* are illustrated the principles of a four-point toggle dwell which has also been used with various modifications, as a drive for drawing presses, as shown in Fig. 290. No toggle dwell is theoretically perfect, but by reducing or eliminating the overpass at one or two dead-center points a more perfect dwell is claimed for the four-point dwell than for the simpler three-point type, Fig. 169. Actually the minute theoretical inequalities in toggle dwells are completely lost in the normal but negligible deflections of the linkages and members of the press frame. The four-point dwell necessarily requires a longer train of moving parts, and it will also be noted at *D* in Fig. 288 that the rise and fall of the blank-holding slide is somewhat steeper than with the three-point linkage.

Fig. 291 illustrates the development which made possible the entry of the hydraulic press into the quantity-production metal-working field. The adjustable stroke to suit the depth of draw and the development of drawing pressure as high in the stroke as required are the desirable features for drawing work. The controllability of pressure is of prime value where bottom stamping is involved. The adaption of punch press shrunk tie rod frames to protect fine tools, in place of the old open rod constructions, has been essential. Placing the reservoir immediately above the rams with normally open prefill valves, positive return cylinders with holding valves and large direct drive, variable delivery pumping units are elements of importance. The cycle of operation permits an economical wide open transition from quick advance to high pressure, to quick return with a smoothness and speed which constitutes quite a remarkable advance in hydraulic press construction.

The "hydro-dynamic" press shown in Fig. 291 is capable of developing working pressures up to 165 tons on the inside or drawing slide, 50 tons on the blank-holding slide, and 20 tons on the hydraulic pressure

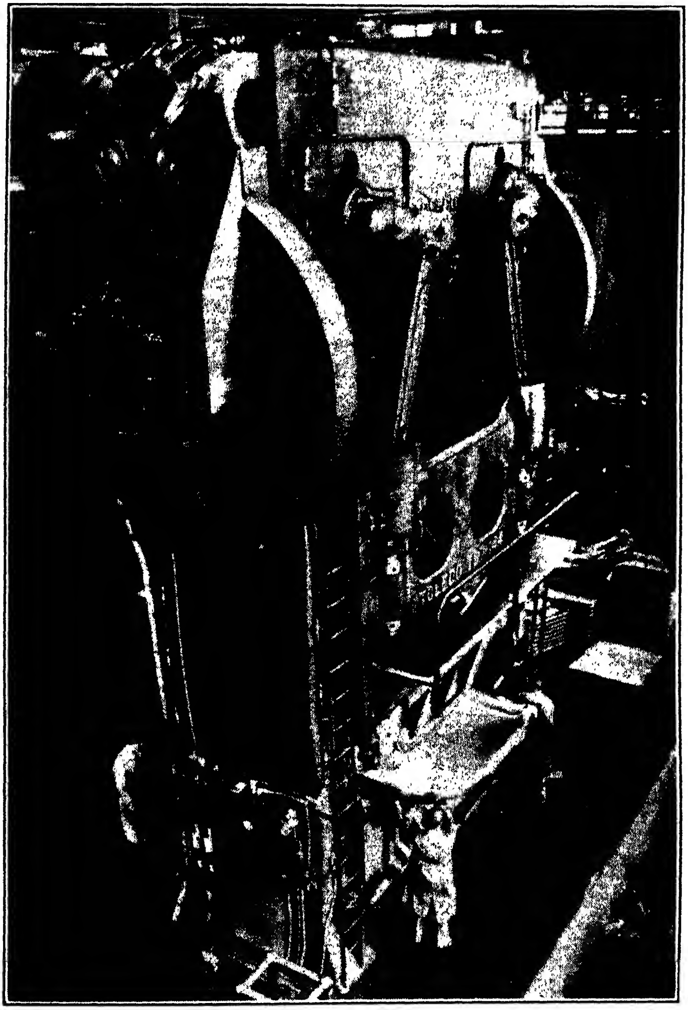


FIG. 290.—A double-action toggle press of the four-point dwell type, fitted with pneumatic pressure attachment in the bed and used at the time to draw the top of an automobile.

pad in the bed. In the production of halves of long oval automobile head lamp shells requiring a 5½-in. deep draw the operator was able to produce 9 shells per minute tripping the press for each stroke with

double palm button controls. A 20-horsepower motor is required to operate the press at this speed.

Triple-Action Operations.—It became apparent fairly early in the history of drawing sheet metal that, for a few jobs, three distinct operat-

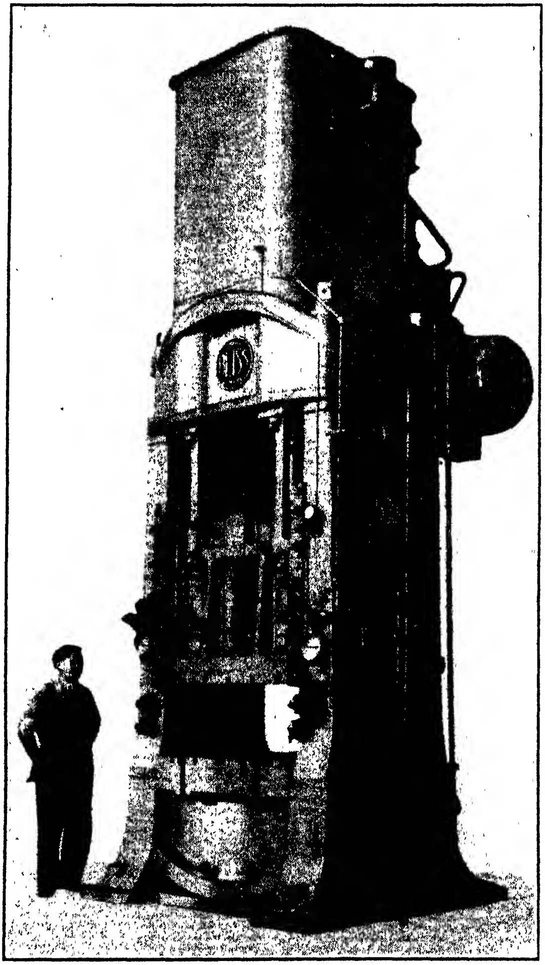


FIG. 291.—A fast-acting double-action hydraulic press for drawing halves of automobile lamp shells.

ing motions would prove either desirable or essential. The usual sequence involved holding by one member, drawing by a second member which subsequently became a holding member, while further drawing was performed by the third member. This may be accomplished by a

single-action press equipped with a compound drawing attachment, a double-action press with a single drawing attachment, or a triple-action mechanical press.

Triple-action methods were early applied to the production of certain cooking utensils and the like where the ductility of the metal would stand two successive draws without annealing. Then came crowned fenders which required two holding actions to prevent wrinkles over the reverse curve. More recently triple-action principles have been applied

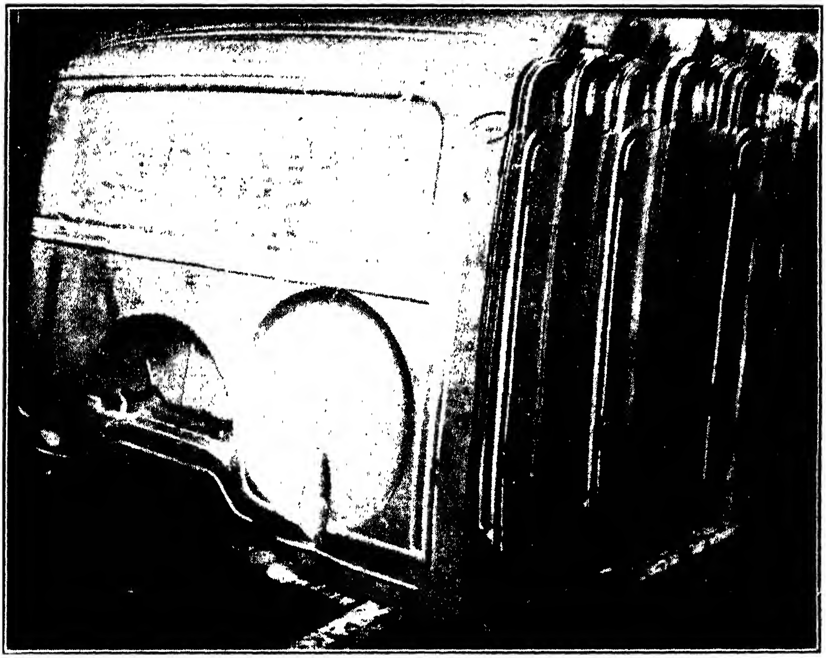


FIG. 292.—A typical triple-action automotive stamping, the side of a light truck body. Note the draw beads and note also how irregular must be the shape of the blank-holding surfaces.

to automobile door and body stampings where an outline shape is drawn first and then a depression for a window or wheel housing is put in as a redraw.

Fig. 292 shows a typical triple-action automotive stamping. Although it involves drawing in opposite directions, it is not a true draw and redraw job in the same sense as a double-drawn cooking utensil. It may be drawn either side up according to equipment available. There is difference of opinion whether the principal draw should be completed first, and then the redraw be started to form the reverse de-

pressions, or whether the draws in opposite directions can be completed simultaneously. This depends in part upon details of the particular shape such as the presence or creation of unsupported areas of metal where wrinkles might occur, or the presence of particularly severe stretching areas which might be relieved after completion of the principal draw as by piercing out a portion of scrap in a window area to permit drawing away from the hole. As it happens, this job was run in a regular toggle-drawing press quite similar to that in Fig. 290, except that it is equipped also with a single-action up-motion redraw press in the base, with interlocked clutch control. The upper press grips and draws the principal shape and stops at bottom center to hold while the redraw press, which has already been started in motion, completes the formation of the depressed areas. Both upper and lower actions move away together and stop with the die space open, ready for the next stroke.

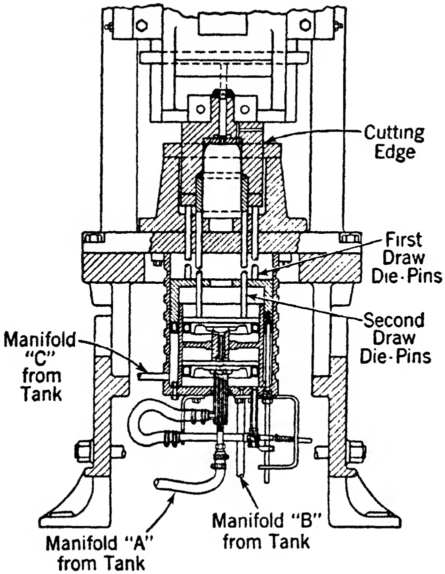


FIG. 293.—A combination (triple-action) blanking drawing and redrawing die in a single-action press with double-action Marquette pneumatic drawing cushion.

Fig. 293 shows a true triple-action combination die for blanking, drawing and redrawing a shell. It is mounted in a single-action inclinable press equipped with a double-acting air cushion. The upper die is shaped for cutting, drawing and redrawing. The lower die includes the usual fixed cutting edge, fixed center plug and a blank-holding ring for the first draw carried on the outer cushion. There is also an inner ring carried on the inner cushion. This remains stationary during the first part of the operation to act as a plug or punch for the first draw. Upon completion of this it begins to move down, acting as blank-holding ring as the shell is redrawn over the fixed central plug. A special mechanical interlock is usually required to support the inner ring during the first draw.

Both the frontispiece, Fig. 1, and Fig. 290 illustrate installations with built-in air cushion drawing attachments on double-action toggle

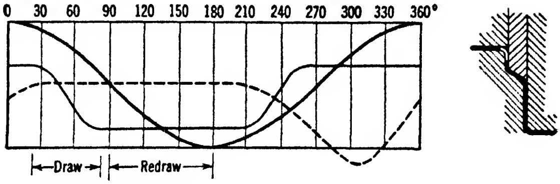


FIG. 294.—Timing chart for a triple-action press such as that in Fig. 295.

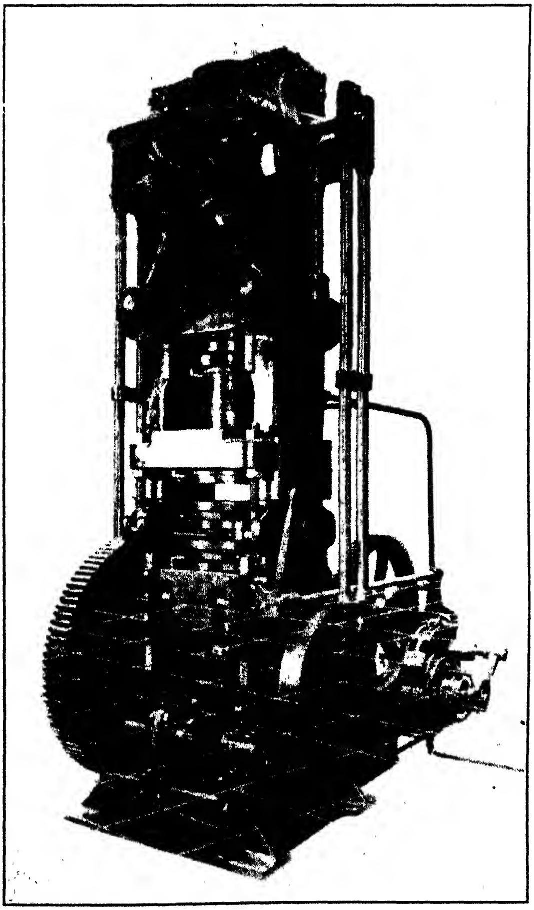


FIG. 295.—A triple-action press in which the die moves up to the under side of the outer blank-holder.

presses. Here the cushions may be used for holding while the outer press slide performs the first draw. This slide then dwells to hold while the inner slide performs the second draw or redraw. A die for an operation of this sort was shown in Fig. 167, page 186. Quite as often the cushion is used to hold a contour pad under pressure against the drawing punch to maintain a shape or to prevent wrinkling.

Triple-Action Presses.—Earlier types of triple-action toggle presses with three down motions would take a die similar to that shown in Fig. 293 except in the inverted position. The die is placed upon the fixed press bed. A ring blank-holder, operated by a pair of toggle-actuated cranks under the bed, is pulled down to hold the blank. A tubular punch actuated by the upper toggles descends to make the first draw and then to hold the shell while the crank-actuated inner punch is pulled down to do the redrawing.

Fig. 294 shows the timing curve for a somewhat different arrangement of triple-action toggle press. A typical machine is shown in Fig. 295. A blank-holding ring is mounted on the under side of a fixed member at about the center of the press. The die, on a lower slide (dotted curve), is moved up against this ring to hold the blank by a combined cam and toggle action. An upper slide, which is toggle-actuated, brings down a ring punch to make the first draw and to hold the shell while the crank-actuated inner punch descends to do the redrawing. These presses have found their principal use in the production of double-drawn cooking utensils.

The four-point triple-action press, Fig. 296, is suited to drawing and redrawing automobile roofs, side panels and doors, complete with window and wheel-house depressions. Here the outer slide descends to grip the margins of the blank while the inner slide makes the principal draw. Then both slides dwell while the third slide in the bed moves up to perform the necessary redrawing or forming of the depressed areas and possibly the decorative beads.

Press Position.—The majority of punch presses stand in an upright position with the reciprocating slide and its driving parts vertically above the die or tool space. Most of the smaller ones, Fig. 41, are arranged so that they may be inclined or tipped back at an angle up to about 35°, Fig. 181.

Whether any press is to be operated in the normal upright position, or inclined to a greater or less degree or even mounted actually in the horizontal position, is largely a question of the work to be done and the quantity of stampings to be produced. Most blanking jobs and many drawing operations are so arranged that the product is dropped through the die to a box or stacker under the bed of the press. Other operations

FIG. 296.—A triple-action press in operation in France. Both inside and outside slides above, and the up motion redraw slide in the base, are of the four-point type with balanced drive at corners for unbalanced loading.

in general leave the product on the surface of the die whence it may possibly be blown off or carried out with the scrap. More often, however, if the press is upright, such parts must be lifted out by hand at the expense of an extra motion and accompanied by some danger to the operator's fingers.

When the production demands become large on work of this sort it is worth while to incline the press and make use of the force of gravity

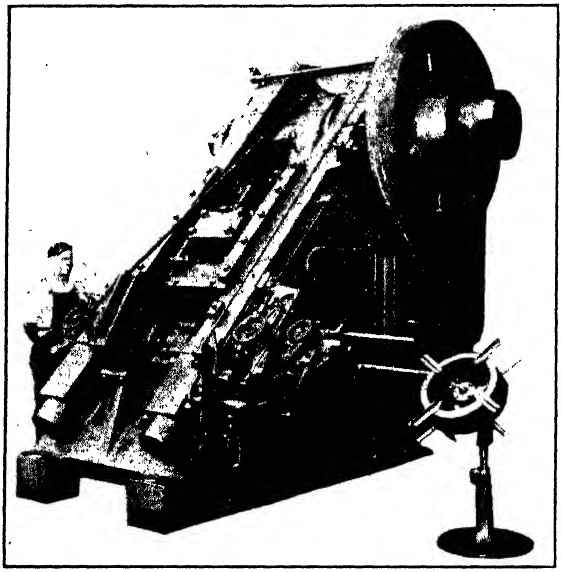


Fig. 297.—A 300-ton high-production unit equipped with high-speed feeds, straightener and scrap shear and inclined 45° to permit discharge of both product and center scrap from the surface of a delicate compound die.

(often aided by an air jet) to discharge the product and possibly to aid in feeding it.

Compound Die Work.—When compound dies are used for flat and accurate piercing and blanking operations, the center scrap is pushed through the die or permitted to slide off from its surface, and the blank is carried up in the punch and discharged toward the end of the up stroke by the positive action of a suitable knockout.

Fig. 297 shows an automatic high-production press making use of the inclined position for continuous operation with a full compound die. This die is very delicate and expensive, so that ejection must be certain to avoid damage to it. Coil stock is straightened and fed across the die by high-speed roll feeds. This stock is lifted after each stroke so that

the center scrap which is left lying on the surface of the die may slide and be blown off. The blank itself is lifted in the punch and discharged about halfway up on the up stroke by means of a cam-actuated knockout to give it more time to fall clear before the next stroke. It is interesting to note that other safety features which are provided include electrical stopping in case the stock cannot feed properly, stop buttons at many points about the machine and provision for stopping both at top center and at an emergency point just before the punch reaches the work near bottom center.

Combination Die Work.—When combination blanking and drawing dies, or combination dies for blanking, drawing and piercing or stamping,

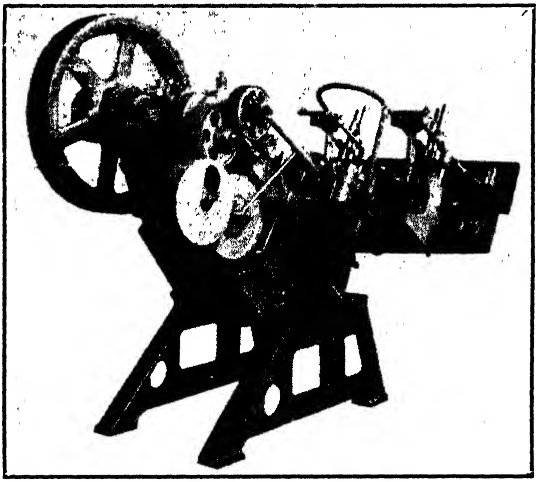


Fig. 298.—A high-speed Bliss suction strip feed press inclined 60° for the ejection of can ends and the like from compound dies.

are used, the shell is normally stripped off the plug in the lower die and hangs in the draw ring in the punch. As the slide moves up it is stripped out positively and permitted to fall back clear of the tools with the possible assistance of an air jet.

Fig. 298 shows a very widely used application of the inclined position to combination die work. Automatic suction strip feed presses, fixed at an inclination of 60° back from the vertical, blank, draw and stamp the tops and bottoms for tin cans from scroll cut strips of tin-plate, and drop them back out of the way from the punch. When operating speeds reach 200 and 250 SPM, air jets are essential to help get the stampings out of the way fast enough.

Many cups, caps and deeper shells are produced in inclined press units which are both hand-served and automatically fed. Notable among these are screw caps for bottles, etc., which are blanked and drawn, usually in multiple in roll feed or strip feed equipments. Often in such cases, especially with brass and aluminum, the limitation upon the production rate is the speed with which the shells can be discharged from the die space. This rate of discharge depends to a considerable extent upon the die layout when three or four pieces are to be produced per stroke.

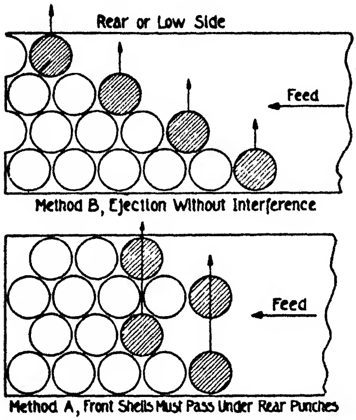


FIG. 299.—Two multiple combination (or compound) die arrangements for inclined presses, method *A* for strip feeding, method *B* for faster operation with coil stock.

Fig. 299 shows, in two ways, the scrap layout and grouping of punches for blanking and drawing four cups per stroke. In the method at *A* the punches are grouped closely together so that half blanks at the ends of short strips can be avoided by skip feeding. There is the distinct disadvantage, however, that shells from the two forward punches must be blown under the rear punches and on out of the way before the punches descend. In method *B*, which is designed particularly for use with coil stock, the shells have only to get clear of the punches in which they are produced, which is much more quickly accomplished. In this method the arrangement can be such that the shells are blown back across the uncut strip as shown by the ejection arrows, instead of across the scrap where they might become entangled. The scrap economy is, of course, the same with either method. In method *B* the tools will always lie on a 30° diagonal with the center line.

Gravity Feeding.—Gravity may be, and frequently is, utilized in feeding shells or blanks into presses as well as in getting them out of the way after the operation. With the press inclined at an angle or actually horizontal, the shell or blank is permitted to slide or fall into a nest gauge on the die surface. If the operation is redrawing the shell may be pushed through the die, or it may be returned to the surface of the die and allowed to drop back through an opening in the back of the nest wide enough to pass the redrawn shell but not the original shell. In piercing operations and the like the blank is usually lifted above the nest

surface by the punch and then stripped off to drop back into a tote box.

Fig. 300 shows an otherwise standard press mounted in the horizontal position and equipped with a gravity chute feed. This particular unit is used for the trimming operation in production lines for Mason jar caps. The drawn caps are delivered by elevator and chute to the chute shown on the press. Here an escapement separates them so that one shell after another drops into place in the nest to be trimmed and pushed out through the die and the bed of the machine. Normal production rates on such equipments are around 70 to 90 caps per minute. It has been noted in some cases at the higher speeds that an air jet is necessary to help the shells to drop with sufficient speed from the escapement to the nest on the die. The ring of scrap stripped from the punch is disposed of by gravity.

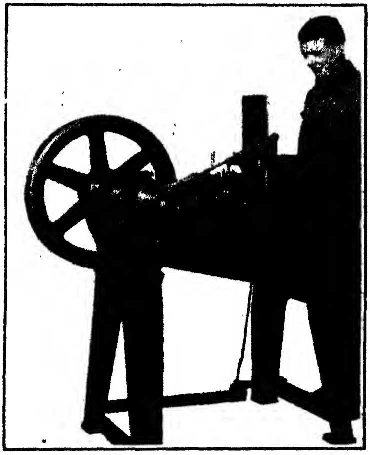


Fig. 300.—A standard press mounted horizontally, with gravity chute feed and gravity scrap ejection.

It should be noted that presses in both the inclined and horizontal positions may be served by double roll feeds, dial feeds and magazine feeds, as well as by hand and gravity feeds.

Inclined Straight-Sided Presses.—The straight-sided type of press has been shown to have a very marked superiority over C-frame types for quantity production work, in point of die life. Presses mounted in the inclined position favor increased operating speeds in the large range of combination and compound die work, because of the assistance given by gravity in feeding blanks and in getting out scrap, as well as blanks, and drawn shells. For that reason, where quantities to be produced are relatively large and where rigid tolerances are specified, the inclined straight-sided press is increasingly popular.

Features and Accessories.—Fig. 301 shows at the left a press used for compound die piercing of motor stator laminations. It illustrates very well both the advantages of the type and a number of points which should be considered in the construction of such a machine.

Dies for the production of motor laminations from silicon steel are always delicate and fussy. Compound dies have some advantage over follow-dies in that the blanks produced are necessarily flat, and since all

related holes are punched together there can be no error due to small differences in location in the several stations of the follow die. In this case a horseshoe nest is provided on the surface of the die. A blank, released by the operator or delivered by a magazine feed, slides down a short table and into the nest which locates it relative to the die.

The bolster plate is arranged with lugs or poppets at the back to support the die in the inclined position. Other lugs, shown at the front of the bolster, keep it from sliding back and provide a convenient adjustment.

To get the stamping out of the die nest it is lifted on the punches and stripped off toward top stroke by a knockout in the press slide. Fig. 301

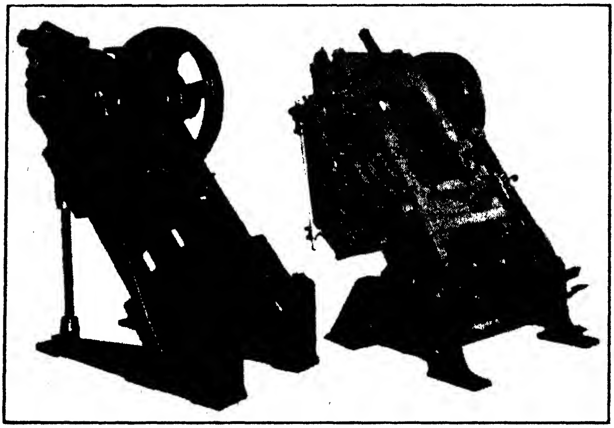


FIG. 301.—Left: To feed and discharge motor laminations, an eccentric shaft press, inclined 45° in a low mounting, and equipped with cam knockout, releasing brake and die support bolster. At the right, standard "high-production" press, with high-speed feeds, mounted on inclinable legs.

illustrates one type of knockout actuated by an adjustable cam which may be timed to strip at around midstroke up, instead of top stroke. This gives an extra time period for dropping the blank out, equal to a quarter cycle, and speeds up the operation proportionately. A similar device is used on strip-feed presses for producing can ends, Fig. 298.

The eccentric-shaft construction, and the built-up frame with tie rods shrunk in under an initial tension greater than the maximum press rating, both contribute to the rigidity which is so essential to the life of fine dies. The releasing brake, which engages only when the treadle is released to stop the press, is a regular feature on continuously running presses to save wear, heating and power loss.

The back edge of the bed is set far down in the legs to keep the press

and die low for convenient hand feeding. The support members from the legs to the frame at the back are solid rod in this case but may also be pipe or cast channel sections. Such supports are used in almost all cases where the press is high and the inclination exceeds 30°. Beyond 60° or 70° the supports are usually replaced by a second pair of legs from the crown to the floor.

Angles of Inclination.—Fig. 301 shows at the right a straight-sided press mounted on inclinable legs so that it may be operated vertically for push-through jobs, or inclined at any angle up to about 34° for blow-off operations performed in combination or compound dies. This

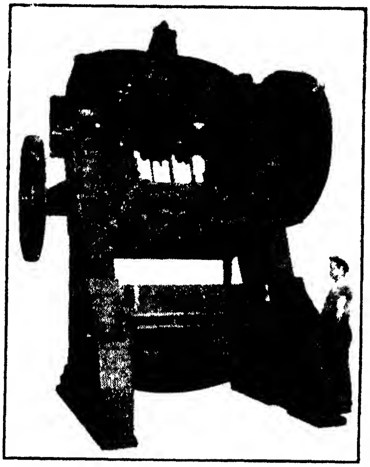


FIG. 302.—A 72-in. wide double-crank press for automotive work, weighing 35 tons and inclined 30°.

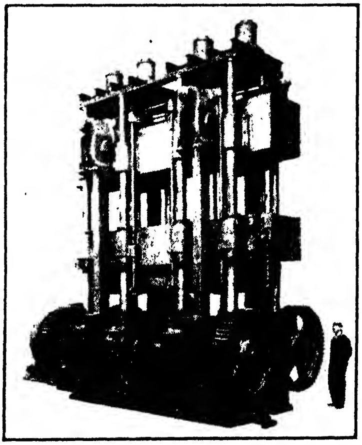


FIG. 303.—A four-crank double-action press with underneath drive, representing the old inverted types.

is one of the massive "high-production" type presses equipped with automatic high-speed feeds for economic quantity production. Owing to the weight of the machine, the inclining mechanism takes the form of a chain hoist attached to the ceiling beams.

Fig. 302 illustrates a fixed angle of inclination of 30° back from the vertical. The machine, in this case, is an 8-in. shaft press 74 in. between housings and weighs around 70,000 lb. It brings forth the fact that size is no particular limitation upon the use of the inclined position when there is an advantage to be gained by it.

For smaller, faster presses where the blank must fall clear more quickly, a greater angle of inclination will, of course, favor a more rapid departure from the path of the punch. Figs. 297 and 301 (left) illustrated the 45° position. Fig. 298 showed a machine inclined 60°. Dis-

posal of both compound die blanks and scrap was the purpose in two cases. Covers blanked and drawn in combination dies were cleared by gravity in the third case.

Other units mounted at extreme angles have been provided with double roll feeds handling stock from right to left through the housings and also from front to back. Many presses, particularly for shell redrawing, are actually mounted in the horizontal position. Figs. 264 and 204 showed large and small presses so placed. For special assembling, double end flanging and upsetting operations, two horizontally mounted presses have been opposed to each other in a common frame so that work could be performed upon each end of the part simultaneously.

The last arrangement to be discussed might be termed the inverted position, as the driving parts are actually beneath the tool space. Possibly this design should have been discussed first as it is found in the early history of almost every type of press. In early mint equipments both the coin blanking and coin embossing presses were of this type. For the former use, Fig. 212, the tool was pulled down; in the latter it was pushed up. Several early makes of cam drawing presses were driven from below. Among the larger machines for banking, forging, stamping and drawing jobs, not a few underneath drives have appeared in both pull and push types. Most of them have disappeared now, however, largely owing to comparative inaccessability of parts for maintenance and operation.

The tremendous forerunner of the wide modern double-crank presses, shown in Fig. 303, is a double-action press, for automobile frame side rails with a pull down slide and a cam-actuated push up mechanism under the bed for blank-holding. The slides are deep and substantial, but the open rod construction cannot be made as free from sway and stretch as the shrunk tie rod type of frame. Picture the floor line at about twice the height of the man to visualize how much of the machine is in the pit.

CHAPTER XIV

AUTOMATIC PRODUCTION

THE harnessing of power to ease human effort more and more, and to provide more bountifully the erstwhile luxuries, has taken place in a remarkably short time. The relatively few million years of the earth's existence, and the very few thousand years since man began to heat and pound metal into useful shapes, still dwarf the century and a half in which present-day manufacturing methods have risen from nothing. In that brief time the first crude steam engines were developed to a point where power became controllable and deliverable at any desired point. Building the engines and building the larger pumps and carriages and looms which the engines could operate created the need which fathered the machine-tool industry. Machine-tool metal-cutting processes made possible the economical building of metal-working presses which have developed their present tremendous utility in the last century. The very brevity of that period assures further great development.

The present era in pressed-metal engineering is developing a wider rise of automatic handling methods and more frequent combinations of stamping operations. Both automatic feeding and multiple-operation tooling require for success a sound understanding of metal-working theory and very careful attention to detail. Any of the typical operations can be put together in a suitable sequence to produce most parts in more or less finished form at one pass. The capacity of the metal to stand the series of operations without intermediate annealing must always be checked. Economy of material is also important in choice of methods, as metal cost is necessarily a major item in the total cost.

The economies of automatic feeding of multiple-operation tools are principally in space saving, inventory reduction, simplified handling, improved production and safety. One press takes the place of a number of smaller ones, each with space for a tote box of parts to be worked and for another box to receive the worked parts. Additional space may be needed for storage of a quantity of parts awaiting the next operation. These same parts-in-process, waiting their turn from one machine to the next, represent a very substantial inventory item and a handling problem of some importance. Hand feeding at each press is ill timed, nervously tiring and quite possibly hazardous.

Fig. 304 shows one of the machines of the new era, a 150-ton press inclined for the rapid discharge of work from the surface of a compound die and equipped with a heavy-duty double roll feed and scrap shear. The job is to pierce and blank an absolutely flat ring from 3/8-in. thick hot-rolled steel. The flatness requires the use of compound dies and the inclined position. The speed of operation is 60 SPM, which is fast considering the cutting edge impact on such heavy gauge. The mechanical feeds and automatic discharge of the work make it possible for the operator to work 10 or 15 tons of material per day.

This is just a part of the process which has been changing our home

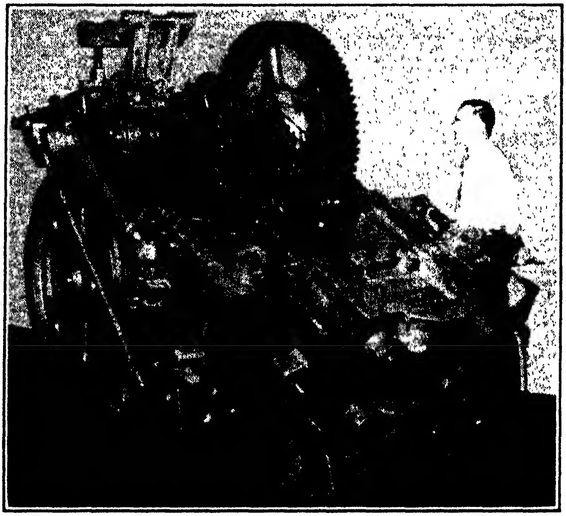


Fig. 304.—An 800 per cent improvement in man-hour production was wrought by this unit in the manufacture of 3/8-in. thick flat steel rings.

life and commercial life so rapidly during the last century. The desire, which is as old as man, to find easier and quicker ways of doing things, is as responsible for the harnessing of the ox to the first crude plow, as it is for the steamship, the vacuum cleaner, the oil burner and the concrete mixer. Mechanical means of travel, mechanical housework aids, mechanical farming implements, mechanical business machines and finally the mechanical equipment for producing all these things have gradually been improving and becoming more common. They all help to make things easier for everyone. Their ultimate result is the higher standard of living which this country enjoys and seeks to improve.

A feed, as in Fig. 305, relieves the operator of any necessity for putting his hands in or near the working area while the press is running. It re-

lieves him also of that nervous strain which is attendant upon feeding a blank into position by hand under a moving punch. Mechanical safety guards are some help, but more often than not they interfere with production, and the operator, who is usually on piece rate, may try to disconnect or circumvent them. In feeding mechanically, however, the operator is loading the blanks or strips entirely away from the danger zone and lost fingers or hands are practically unheard of.

The strain of hand feeding accounts for another advantage of automatic feeding which is often overlooked. Mental fatigue makes the operator lose frequently as much as 10 or 15 minutes out of every hour. The mechanical feed, on the other hand, plows along hour after hour, catching every stroke of the press. Its overall efficiency, aside from tool changes, may be 95 or even 100 per cent, depending upon the method of loading.

FIG. 305.—Starting strips to a gauge point with the press running continuously at 325 SPM, the operator is under no nerve strain as his hands are never in danger.

Fig. 306 shows a unit which may be run at practically 100 per cent efficiency between tool changes. The operator acts principally as a guard, watching the progress of work through the multiple-operation press and the thread rolling machine which is tied in with it. Occasionally he refills the hopper or removes finished shells.

The hopper should never be empty, and the flow of parts should never stop except for mechanical failure or tool replacement.

The part is a lamp socket. In a previous operation a roll feed press blanks and draws three shells per stroke, for scrap economy. These shells are fed to the hopper and thence automatically through the press and thread roller in Fig. 306, for a series of six operations. The operations include, for example, redrawing, restriking, piercing, trimming, burring and rolling the thread.

Fig. 307 illustrates another typical automatic unit of the new era, and is incidentally one with an interesting record. It is a "high-production" press of 50 to 75 tons rating. Designed for short stroke work at speeds up to 250 SPM, it has a notably chunky and compact frame, of the straight-sided type, assembled with rods which are shrunk

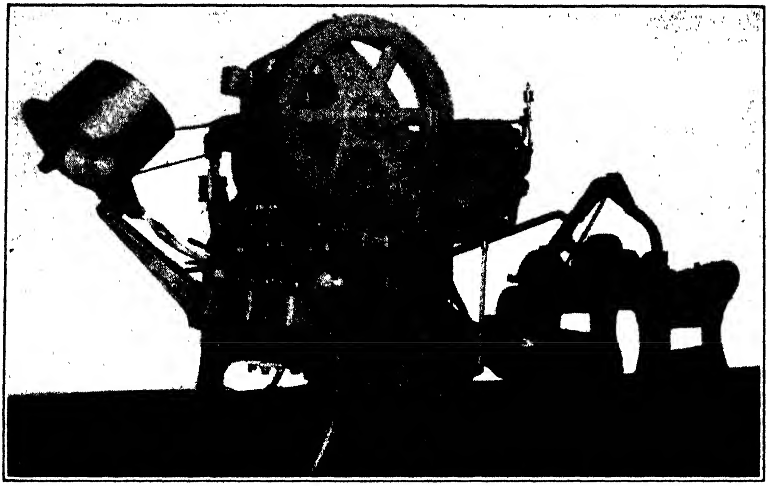


FIG. 306.—Approaching 100 per cent efficiency. A practically unbroken stream of shells passing automatically through a series of six operations including rolling a thread.

in place under a permanent stress well beyond the maximum rating of the machine. The full eccentric shaft is supported up to the pin at the sides by internal crown ribs and the main bearings. The high-speed double roll feed and the scrap cutter are very compactly built into the press. The necessary adjustments have all been developed to a point where they are very accessible and convenient.

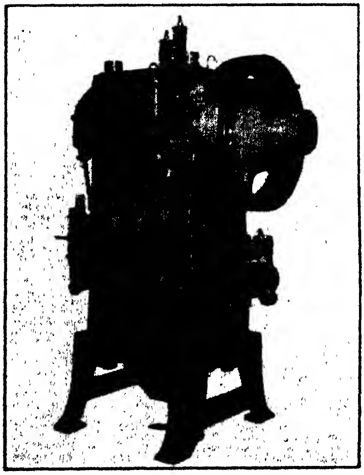


FIG. 307.—A rugged and compact "high-production" press with built-in feed rolls and shear all highly developed for convenience of adjustment.

This press (Fig. 307), taken from a stock lot, has been in operation for about two years in an American plant of an international corporation. In that time it has been operating at 225 to 275 SPM, frequently two shifts daily, and has not even been bolted down to the floor. That point speaks volumes for the balance and stability of the unit. The operation is piercing, forming and blanking light gauge copper-coated steel from the coil and cutting up the scrap.

Production records show an average die life of 900,000 to 1,000,000 punchings per grind, and a total of around twelve million per die. Exceptional as these figures seem they are indicative of the results being obtained from the new types of " machine tool " press equipments.

In a discussion of feeds in 1925, C-frame or inclinable presses were stated to outnumber those of the straight-sided type in the ratio of 13 to 5. Attention was called to the already well-established fact that the straight-sided type of press gives for most purposes much better tool life than the C-frame type. It is therefore superior for quantity production work where mechanical feeds counteract the all-purpose convenience of the C-frame press. A growing realization of this advantage, and the development of new types and arrangements of feeds for straight-sided presses of various sorts, have resulted in more or less reversing the ratio, as indicated by illustrations in this chapter.

Speed of operation in automatic equipment may be determined by any one of three limiting factors, i.e., (1) the maximum speed of the presses available, (2) the fastest feeding speed possible within limits of accuracy which permit successful piloting, and (3) the greatest contact velocity of fine punches, cutting edges and drawing surfaces consistent with reasonable tool life. Many structural details necessarily enter for consideration in each case.

(1) **Press Speed.**—Mechanical limitations upon the speed of the press may develop in the stroke, the clutch or the drive. The lineal velocity of the crankpin, which is the same as the velocity of the slide at midstroke, is usually between 25 and 100 ft. per min. Special cases of crankpin velocities up to about 200 ft. per min. have usually involved special press constructions with decreased weight (inertia) of reciprocating parts, increased mass of fixed parts and generally improved balance and stability. Many such presses are shown, including particularly those of the " high-production " type.

Geared-drive presses are naturally not so fast as those which have direct drive to a flywheel on the crankshaft. Back shaft speeds are normally 350 and 400 RPM and occasionally up to 1000 RPM—a speed which has been made possible largely by the use of Timken bearings and the like. In such cases care must necessarily be taken in balancing the flywheel as a serious lack of balance would set up a pound on the bearings. Gray-iron flywheels are regularly limited to a peripheral velocity of about 5000 ft. per min. on account of centrifugal strains.

Positive clutches are commonly used on most of the smaller and faster presses. Friction clutches are desirable, especially for die-setting purposes on the larger presses, which are too heavy to turn over by hand.

They require a fairly high ratio of gearing to keep them down to an economical size and still maintain an ample driving surface for safe friction loads, long life and smooth operation.

Fig. 308 illustrates the rolling key clutch, one of the positive type which has been particularly successful for high-speed operation. The reasons for this are again traceable to questions of impact, inertia and balance. Engaging velocities are much lower than in the case of pin and

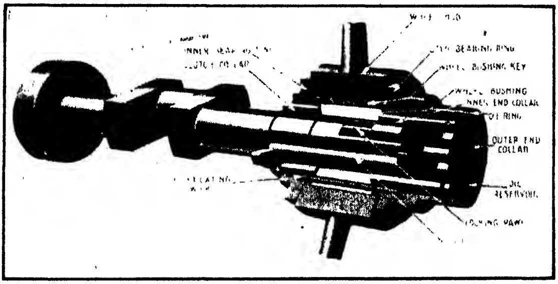


Fig. 308.—The Bliss rolling key clutch, a positive type which is so constructed that the smaller sizes are used up to speeds of 300 and 400 SPM.

jaw type clutches because the engaging surfaces are very much closer to the center line of the shaft. There is no wearing side twist to the wheel upon engagement as the driving members are exactly balanced with reference to the central plane of the wheel and between its bearing rings. Engaging surfaces are necessarily made of tough alloy steels hardened and drawn back. In disengagement, the inertia of the fast-moving shaft and connections makes it desirable to provide for considerable override of the latch on the dwell surface of the clutch hook while a large releasing brake is absorbing the excess energy and bringing the parts to rest.

(2) **Feeding Speed.**—Roll feeds are a relatively fast type of feeding mechanism, but even so wide differences in results are obtained, according to the design of the particular unit. A convenient means of comparing feeding speeds is to multiply the feed length required, in inches, by the number of feeding strokes per minute. Thus the older types of stock roll feeds for C-frame presses might be expected to feed within close limits up to about 400 in. per min. and to feed within limits easily corrected by piloting up to 600 in. per min. The high-speed feeds used on the " high-production " line and incorporating many refinements will handle about 700 to 1200 in. per min. of nominal feeding speed. A special patented roll feed for extremely high feeding speeds, especially in the production of automobile radiator fins, is shown in Fig. 309. It will feed accurately at 2000 in. per min. or more.

These nominal feeding speeds are only about a third to a quarter of the actual peak speeds reached at the middle of the feed stroke. Feeding speeds depend principally upon the inertia of the moving parts, the efficiency of the means for absorbing this inertia during deceleration and the elimination of lost motion in the drive train. Many details of feed, die and reel construction may also affect the results to some extent. Where heavy coils are used it is often vital to drive the reel to avoid inertia jerks in starting the coil in motion, which are likely to cause a misfeed.

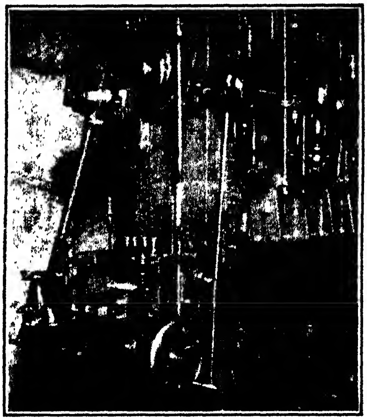


Fig. 309.—Accurate feeding at speeds around 2400 in. per min. is the feature of this patented feed for radiator fins and the like.

(3) **Punching Speed.**—Fig. 310 shows a collection of pierced and blanked parts produced at relatively high speeds in automatic equipments. In almost every case the limitation upon further increasing the speed was the impact upon the cutting edges, especially of delicate punches. Only in the case of the 0.010-in. steel part in the upper center could the tools have stood a speed higher than the upper limit of the press speed.

The prediction in advance of maximum cutting speeds is an interesting problem which will bear further investigation. The variable factors obviously include the material used in the tools, the resistance of the material to be cut, the velocity of the punch just as it strikes the work, the rigidity and alignment of the press, delicacy of the punch and provisions made for lubricating and cooling it.

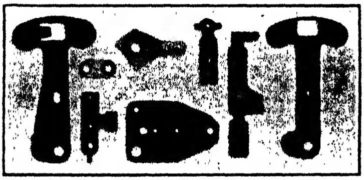


Fig. 310.—Parts pierced and blanked at high speeds. Cutting edge impact on fine punches precluded further advances in speed.

An effort has been made to combine the more tangible of these factors into chart form, Fig. 311. Here we have combined the distance above bottom stroke that the punch strikes the metal, the press stroke and speed to give the speed of the punch at the instant of contact and then multiplied this by the metal thickness and its shearing strength to give the resistance which the punch

meets per inch of cutting edge, as a unit length. The result is a factor for the blow on the cutting edge which should be fairly constant under common press and tool conditions.

To check up the results, data were collected, Table XXIII, upon a fairly representative group of production operations. These were selected as quantity jobs being run in first-class tools which had been speeded up about as fast as seemed to be consistent with satisfactory tool life. In the table several samples of silicon steel have been separated from the rest of the group as the material is notably hard on tools. At the other extreme are a group of very heavy gauge, relatively slow-moving jobs. For the remainder it seems significant that the five variable factors shown on the chart, with a considerable range of values in each case, can be united with relatively so little spread in the results. It will be remembered also that delicacy of tools and judgment in the matter of limiting speeds enter into these figures.

On the chart, Fig. 311, an example has been indicated with dotted lines to show the method of reading it. First pick out the working stroke or the distance up from bottom stroke that the punch strikes the metal. This includes the metal thickness plus the distance the punch will enter the die. In the case of combination dies the punch passes the cutting edge by the full depth of draw or even more if there is no flange. From the proper value on the lower left scale travel horizontally to the curve for the desired stroke; then vertically to the correct speed line; then horizontally right across the contact velocity scale to the metal thickness line; then down vertically to the shearing strength of the metal in question and then horizontally to the right to obtain the value for the blow on the cutting edge.

If it is desired to determine a proper speed limit for a new job, a value for the blow may be selected with the aid of Table XXIII or other data on file and the process worked back from both ends to the intersection of the vertical and horizontal dotted lines at the proper speed value.

A formula to arrive more accurately at values read approximately from the chart may be written either

$$B = \pi \times d \sin a \times t \times S \times \text{SPM}/12 \tag{39}$$

or

$$B = 0.5233 \times t \times S \times \text{SPM} \times \sqrt{dy - y^2} \tag{40}$$

in which B = blow on cutting edges in pound-feet per minute per inch;

d = press stroke in inches;

a = angle up from bottom stroke at which punch strikes;

t = metal thickness in inches;
S = shearing resistance of metal in pounds per square inch;
SPM = strokes per minute of slide (continuous rating);
y = distance up from bottom stroke at which the punch strikes the metal.

TABLE XXIII

BLOW ON CUTTING EDGES

Work	Metal	Thickness, inch	Stroke, inches	Speed, SPM	Blow ft.-lb./min.
Motor lamination	Silicon steel	0.018	1.5	225	30,000
Transformer lamination	" "	.014	1.5	240	30,000
Notching, rotors	" "	.014	0.75	600	25,000
Extrusion blanks	Zinc	.135	1.5	70	50,000
Grill perforating	C.R. steel	.063	2.	75	50,000
Chain links	Steel	.034	1.	330	65,000
Sewing machine	C.R. steel	.060	1.5	125	70,000
Can ends	Tin-plate	.015	3.	200	65,000
Washers (example)	Steel (skelp)	.10	1.5	100	115,000
Extrusion blanks	Aluminum	.125	1.5	250	80,000
Switch parts	O.H. steel	.125	1.5	125	155,000
" "	Copper	.125	1.5	200	150,000
Key blanks	Hard brass	.081	2.	100	81,000
Door latch	O.H. steel	.078	2.5	165	165,000
Ball race	H.R. steel	.375	2.	60	420,000
Coal screen	O.H. steel	.250	2.5	45	246,000
Drum blank	O.H. steel	.312	4.	15	167,000

Drawing Speed.—The determination of press speed as limited by the tendency of the dies to pick-up or load in drawing is discussed in Chapter IX, page 193, and also in connection with Charts XII and XIII in the Appendix.

Follow-Dies.—A part of the impetus to the new era of automatic feeding is attributable to an increasing familiarity on the part of the trade with the principles and details of follow-die construction. Generally speaking, a follow-die is a combination in a single holder of a number of operating stations for the performance of a series of operations in the production of the desired piece. In such a die the piece is usually

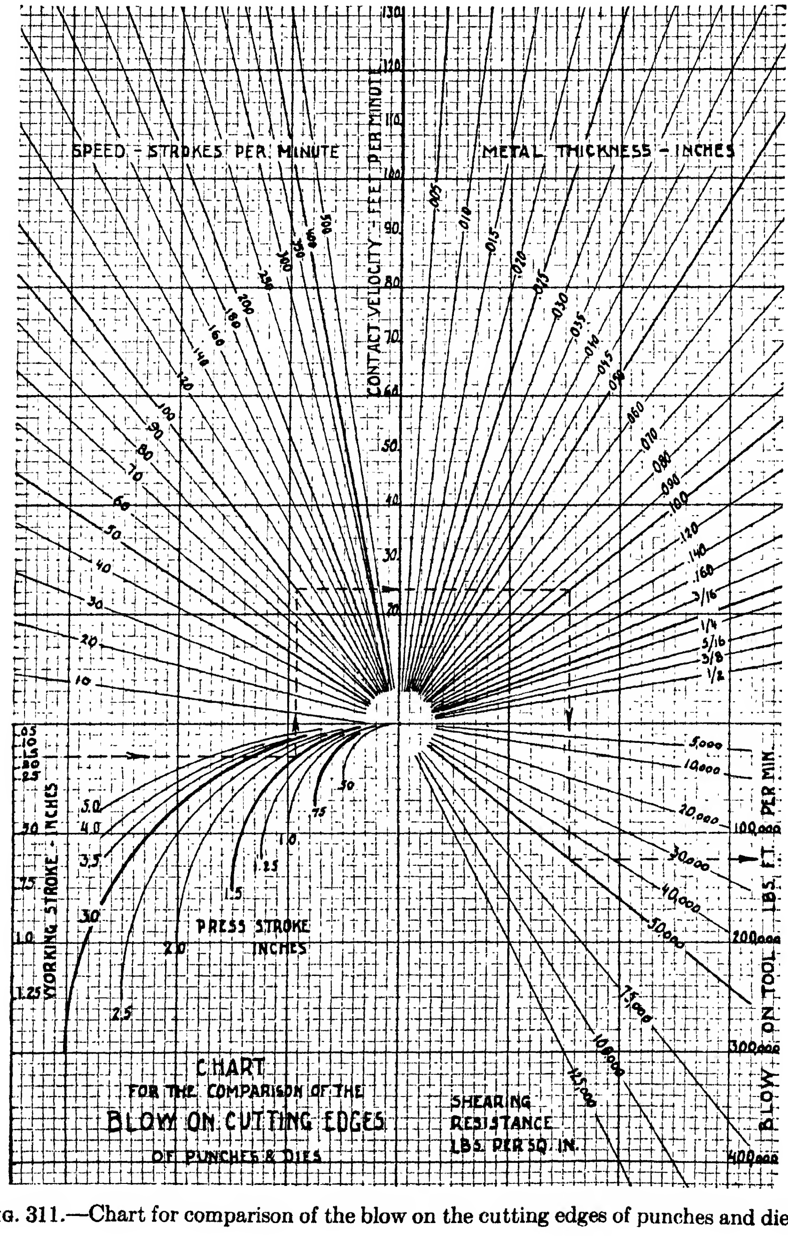


FIG. 311.—Chart for comparison of the blow on the cutting edges of punches and dies.

kept attached to the skeleton scrap or to the next piece until it is completed and sheared or blanked out.

The fact that a number of operations are combined in a single tool instead of being performed in separate presses obviously results in considerable savings in handling charges, storage space and work-in-process inventory. Similar advantages accrue in the use of multiple-slide transfer-feed presses for performing a series of operations upon parts which cannot be kept tied together or to the scrap while in process. A small machine of this type was shown in Fig. 175; others will be shown later. The economies which result from combining several operations in a follow die or a series of dies in an automatic press should not be

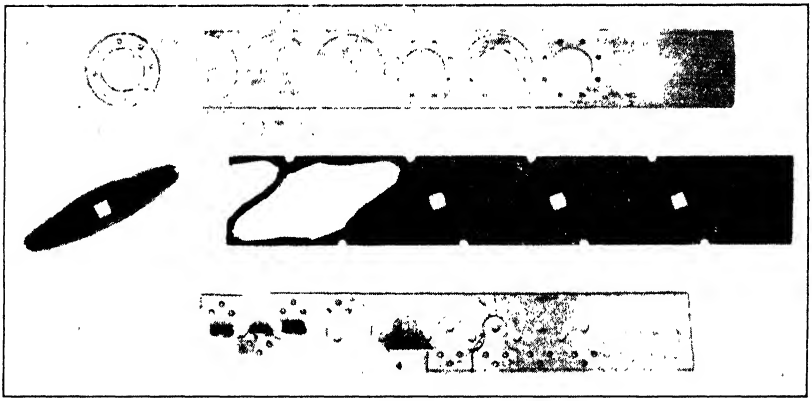


FIG. 312.—At the top, a 2-in. diameter, roller bearing end-ring pierced, blanked and pushed back, flattened and pushed out at about 225 SPM. Center: A bumper clip; pierced; blanked coined and pushed back; (idle); drawn and ejected. Such a blank might also be carried on top of the scrap. Bottom: Two angle brackets produced per stroke without any scrap margin, in a single roll feed "high-production" press.

permitted to obscure other savings possible in single or multiple dies for blanking, compound piercing and blanking or combination blanking and drawing in suitably arranged automatic presses, such as the compound die unit, Fig. 304.

Operations of the shearing group which may be and are performed automatically include a very wide variety. There are, of course, many plain blanking jobs and piercing and blanking operations either single or multiple. Many others include also some bending, forming or drawing operations.

In general the best rate of production is to be obtained by the use of roll feeds and follow-dies, keeping the part attached to the scrap in one

way or another until it is finished and pushed through the die or positively ejected from its surface. There are a number of interesting methods of accomplishing this. For various reasons it may be necessary to pierce out between blanks, leaving only a skeleton of scrap to carry the work, or to slit around the work, leaving it attached at only one or two points, or to cut out the blank and push it back into the scrap for transportation across subsequent stations. These and other " stunts " in the design of cutting tools often make it possible to develop rather simple tools to produce in finished form quite complicated stampings without a second handling of the material.

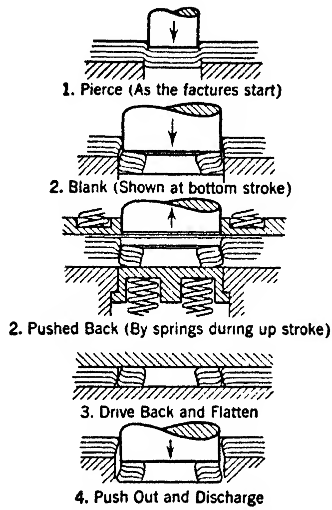


FIG. 313.—Diagrammatic sketches of sections referring to Fig. 312 to illustrate conditions at the sheared edge in push-back operations. Thickness exaggerated for illustration.

Blank and Push Back.—Figs. 312 and 314 show interesting jobs in which the blank is sheared out completely and then forced back into the strip but with different purposes in view. In each case coil stock is handled in " high-production " presses equipped with high-speed roll feeds, Fig. 249.

Fig. 312 (top) shows the operations in the production of an end-ring for a roller bearing. It is specified that this ring must be practically flat. A compound piercing and blanking die to produce the part complete at one station would give the desired result. But such a die would be weak and would have to be run in the inclined position with gravity discharge from the punch surface which would slow down the operating speed to, say, 100 or 125 SPM. An ordinary follow-die to pierce and blank the part out through the die would be the natural solution for speed. In such a case, however, the blank would be seriously dished or bowed as suggested at the second station in Fig. 313. The amount of bow is greater for softer material, for more clearance between punch and die and for greater diameter of the pierced hole in the center of the blank. The bowing is in effect a bending of the relatively free inner edge during the plastic working period before the fractures start in shearing.

For that reason the method shown at the top in Fig. 312, and again in section in Fig. 313, was selected. The operations are: (1) pierce all holes, having the small punches stepped about one-third of metal thick-

ness shorter than the center punch to avoid spreading strains; (2) blank the part, preferably without pushing it quite out of the scrap, and then, as the punch recedes, force it back into the scrap by means of stiff springs under the die and above the stripper; (3) drive back, stretching the scrap to get room, and flatten the blank between plain surfaces; (4) push the flattened blank out through the die, there being relatively little edge friction to overcome. The scrap is then fed on through the outgoing rolls and sheared up in the scrap cutter.

In the center in Fig. 312 is shown a series of operations in the production of a bumper clip of quite heavy gauge steel from the coil. It will be noted that the operations are (1) to pierce the center hole and pilot notches, (2) stamp the countersink around the center, blank down and push back under spring pressure, (3) idle or possibly strike back even tighter, (4) draw and strike, return to the surface of the die and discharge. The operation is performed in a " high-production " automatic press mounted in the inclined position as at the right in Fig. 301.

The drawn sides of the part are quite low in spots, which makes a good drawing job difficult, and the bottom of the shell has a gradual curvature in two directions so that the above procedure (bottoming in the drawing die and discharge from the surface) may have been essential. An alternative which should be considered, however, would be: (1) to pierce as before, (2) stamp the countersink and shallow surface curvature, (3) blank and push back, (4) idle, (5) draw and push through. This would mean raising the strip a little during feeding but would eliminate the inclined feature and also the gravity or air discharge of the piece from the surface of the die.

As illustrated at the push back station (2) in Fig. 313, the largest diameter of the blank is greater than the smallest diameter of the hole it comes from, by the clearance or difference in diameter of the punch and die, or even a little more than that owing to the spring back of the burnished surface metal after strains have been relieved by the fracture. Therefore a blank cannot be pushed back flush as at (3) in Fig. 313, or pushed back through the hole without stretching the surrounding scrap. Experience seems to have shown that, in order to make it easier to push back flush and thereby reduce the chance of dropping a blank in transit, it is desirable to keep the surrounding scrap thin as in the first two cases in Fig. 312, so that it can be stretched fairly easily.

It may be noted that if these jobs had been in thinner metal it might have been desirable to shear the blank up instead of down, so that it would rest on top of the scrap in transit instead of being carried by edge friction in the under surface. This practice should not interfere with drawing a blank down through the die.

It is naturally easier to keep a blank in the scrap if it is fairly thick compared to its diameter and if it has irregular notches and tongues to lock into the scrap. Below 0.020 or 0.030 in. thickness it is rather difficult to keep even a small irregular blank in the scrap.

The use of an odd shape to lock a part in the scrap is shown at the bottom in Fig. 312. The piece is a 16 gauge steel, hinge bracket with raised points for spot welding. Originally the sides of the prong were parallel, which was changed by increasing the end diameter by 1/64 in. and decreasing the neck width by 1/64 in. This gave enough of a locking effect so that the piece would not work out to the side when blanked and pushed back.

The strip in the illustration is shown upside down, the base of one bracket and the prong of the other being bent down into the die. As these meet with no obstruction in traveling in the direction of feeding it is unnecessary to lift the strip. Coil stock is moved by single roll feed across the die to a stop at the end. The operations, as shown,

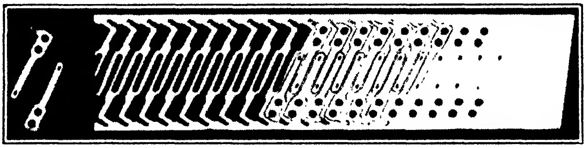


FIG. 314.—A fussy follow-die job in which two light gauge spring brass parts are pierced, blanked and returned, bent and finally pushed out.

are: (1) pierce both center holes and stamp indents for one bracket, (2) pilot, (3) blank one bracket and push it back into the strip, (4) strike back flush, (5) bend one bracket, (6) push out and drop through, (7) indent the other bracket, (8) bend the other bracket, (9) shear off the other bracket and drop through. With brackets of this sort which may interfere with feeding if they do not drop clear sufficiently quickly, it is often desirable to furnish spring-backed ejector pins in the face of the knockout punches.

Owing to spreading strains in the stock during blanking, it is natural for a strip which is being notched on one side to twist or bow toward the other side. Such an effect in Fig. 312 naturally tends to cause an error in location of the bend in the eighth station. To keep the strip straight a punch was arranged to coin a slight groove near the long edge of the strip opposite the blanking station, with the purpose of stretching the metal there enough to compensate for the stretch due to blanking.

Fig. 314 shows a blank and push-back job with a number of interest-

ing features. This job presented serious problems in its solution, principally because of the difficulty of holding two delicate parts in 0.015-in. spring temper brass through a number of stations. The layout was selected as being the most economical of material and producing a part free from corners or slivers such as might be produced by slitting around the tab which had to be bent and then trying to match cuts at the blanking station. The working operations were: pierce, pilot, blank and return to the scrap, bend the tabs (down), push out, feed on through a second pair of feed rolls and cut up the scrap. A number of idle stations were put in where necessary between the working stations to give strong die steels.

The number of blanks pushed back caused considerable warp in the strip for a distance of about 3 in. Hardened stops or distance blocks were furnished to prevent the punches from entering too far so that the blanks might not return properly to the strip. The spring stripper capacity exceeds 1000 lb. Both tabs are bent down. On one side the tab feeds away from the bending die steel through a groove in die which is cleared through to the knockout station. On the other side the bending die steel is made a part of a slide which is moved in and out by a wedge cam motion in the tool to permit the tab to feed past without the need of lifting the strip.

Note in Figs. 312 and 314 that care must be taken in starting each new coil not to leave part blanks lying on the die to catch or mark up the succeeding production. A patented starting mechanism provided on "high-production" presses includes a treadle shown at the right in Fig. 317, a cam on the press shaft to control the time at which the feed starts and means of gauging the location of the end of the strip. With this device, the operation at the top in Fig. 312 can be started so that the end of the coil will coincide with the scrap margin between blanks in order that the first blank may be a full blank with scrap all around it to keep it from falling out. A job of this sort might even be run continuously with strip stock if the scrap margin were increased a little and the length of strips were controlled closely to a whole multiple of the feed length.

Inspection of the scrap end of Fig. 314, however, indicates that there will be a number of small loose pieces left by the blanking operation which do not have scrap all around them and are therefore likely to fall out and lie in the die. This is prevented in starting practice by snipping the end of the coil at an angle so that there will be only two loose pieces to remove; running the press three strokes; removing the strip; knocking out the loose pieces by hand; and restarting the strip. As a matter of fact, in this particular case, the strip was removed again after three

more strokes and the first few whole blanks were knocked out to insure a good grip when blanks reached the bending station. This sounds complicated, but owing to convenience of the starting mechanism only two minutes was required for loading a new coil on the reel, trimming and starting it. A 24,000 blank coil runs for 40 minutes before the next change. And if the metal is heavier the starting procedure is simpler even though the blanks may be interlocked for scrap economy.

Piercing and Slitting.—In discussing piercing and shearing operations, particularly with reference to follow-dies and automatic operation, it has been pointed out that the best production is usually obtained by carrying the part in the strip to retain positive control of it until completed. One of the methods mentioned for freeing the blanks for subsequent operations in such a series was piercing or slitting around parts of the blank, leaving it attached at other points.

The principal problem in most such cases is the matching up of cuts to give a smooth outline and to avoid slivers and bad corners of various sorts. When one cut made in one operation is to join an edge or opening produced in a previous station it must be remembered that the metal may stretch by different amounts in the same operation, the width of commercial strip stock is subject to variation and pilots may not and usually do not fit closer than 0.001 or 0.002 in. All these factors will contribute to possible misalignment of matched cuts, resulting in steps, notches or slivers. Such troubles can be avoided or minimized, however, by proper design of parts and operations.

Figs. 315, 316 and 317 show an interesting job into which the matching of cuts enters at two stations. The part is a hard brass spring member formed with curvature in both directions and has tabs at each end which must be capable of a right-angle bend and back, repeated two or three times. When laid out for quantity production it was originally planned to feed the part in the short direction in order to get a maximum feed speed and use wide stock. This brought the bend across the tab parallel to the grain of the metal. Spring temper stock, eight numbers hard was required for the strength of the part, but such material would not stand the necessary bend test with the grain as was discussed on page 86.

Accordingly the layout had to be changed to feed the long way of the part in order to bring the tab bend *across* the grain of the stock. The sequence shown in Fig. 315, in which two parts are produced per stroke, was selected in order to obtain the production originally planned and yet slow down the press speed to get a reasonable feeding speed for so small a pilot. That is, the original plan called for about a ½-in. advance at 400 SPM or a nominal feeding speed of only 200 in.

per min., whereas in the revised scheme with nearly a 3-in. feed at about 250 SPM the nominal speed of feeding was 750 in. per min. and the production was about 500 pieces per minute.

For economy of material the layout was planned practically without scrap except for necessary piercings and the small loss between blanks

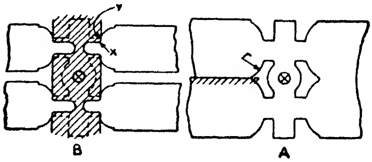


FIG. 316.—Details from Fig. 315, showing at A the run-out of the slitting cut to avoid slivers and at B the parting cut overlapping the pierced holes to avoid corners or steps.

FIG. 315.—The sequence of operations in producing two springs per stroke from spring temper coil brass.

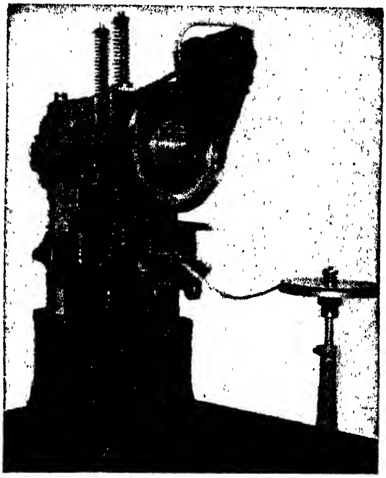


FIG. 317.—"High-production" press and die used to complete about 500 clip springs (250 strokes) per minute; *see* Fig. 315.

in parting of the completed springs. As this leaves no scrap to pull by, all feeding must be done by the pushing across the die with a single roll feed (Fig. 317). This brings forth another advantage in the arrangement shown in Figs. 315 and 316, as the bar of scrap tying the two production lines together makes the strip quite stiff.

The sequence of operations was: pierce openings to outline the ends of the blanks; idle; slit the two blanks apart, letting the cut run out into the pierced openings at each end; form the two parts complete; idle; part out the scrap bar freeing the two finished parts, all as shown in Fig. 315.

Note at *A* in Fig. 316 that, if the two radii (*r*) had been brought together to a practically sharp point, the punch would have been difficult to maintain, and it would have been practically impossible to keep the slitting cut from running out a little one side or the other of the point leaving a very sharp and dangerous barb or sliver. Accordingly a very narrow step or flat was permitted to give some leeway for the runout and a corresponding notch was inserted at the outer edge for symmetry.

Note at *B* in Fig. 316 that the corner *X* of the parting punch is arranged to overlap the corner *Y* left by the piercing punch by enough so that a small mislocation will not be noticeable or leave any notch.

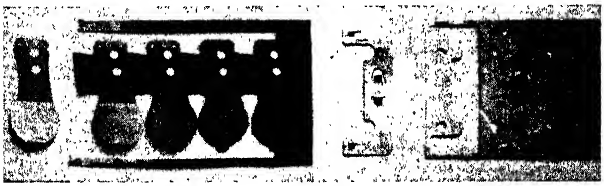


Fig. 318.—At the left, overlapping piercing cuts free the part for forming, after which it is blanked through the die. Cuts must be matched at six points. At the right, light spring steel part having tabs bent with the grain. Pierced slots free tabs and protect corners.

Fig. 318, left, shows the steps in the production of a 0.014-in. spring steel part from coil stock. In the first step two large and two small round holes are pierced. Next to them are two irregular piercings which outline half of the profile of each of two adjacent blanks, except for a band of scrap which is left to tie the blanks together. These outline piercing cuts overlap progressively and have rounded corners in order not to leave sharp steps in the part where the cuts meet.

In the third step the part is struck in a hit-home die to make the three bends in the ends which are now free. This blow is repeated in the fourth step to make certain of the angle. The strip is shown upside down in the photograph as the large end of the part is bent down into the die. In the fifth position the finished part is blanked down through the die, leaving the small scrap bridge piece lying on top of the die, or rather sliding off in the direction of feed.

The bands of scrap at each side were left to permit double roll feeding, pulling as well as pushing. It seems debatable on this job, however, whether it would not have been better to use 11 per cent narrower stock, saving that much material. In that case the outline piercing punches would become notching punches, with comparatively little change to the tool except to provide heels to take the offside shearing thrust on these punches, and to move in the side guides. Spring stock is reasonably stiff, but a little greater care might be necessary in the arrangement of guides to prevent any possibility of buckling between the feed rolls and the die.

Certain troubles were experienced in getting the die into production, but it was finally run at 400 SPM in a No. 630 " high-production " press. There was some tendency for odd-shaped pierced scrap to suck back with oil on the punch surfaces and work over into the stamping station to blemish the subsequent product. This was overcome by shearing the punches sufficiently to break the oil film.

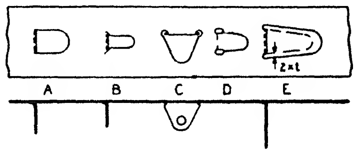


Fig. 319.—Several methods of producing tabs or lugs, the relative merits of which are discussed in the text.

The coils were wound on about 20-in. inside diameter which was ample for feeding without straightening. Inexperienced handling resulted in some of them being dropped and kinked eggshaped or elliptical. When fairly sharp kinks came into the die they would throw the free end of the strip either up or down so that on the next feed there might be a jam due to catching either in the punch or die openings. This was overcome by care in handling the stock but might equally well have been prevented by substituting a close fixed stripper for a portion of the spring stripper.

It is the writer's feeling that these little difficulties are of interest in view of the increasing use of follow-dies and fast automatic presses. To feed properly, stock and parts must move freely, locate properly, strip positively and drop freely at every step. That sounds elementary, but such difficulties as are experienced in tuning up dies for such work almost invariably trace back to an oversight on some simple point.

Slitting and Bending Tabs.—Figs. 318 and 319 illustrate a number of interesting points in the design and production of tabs for various purposes. The operations may be one, two or three as desired. To slit and bend a tab in one operation, the bending radius must be restoned every time the slitting punch is reground, and there is likely to be side thrust due to bending which may bother the cutting edges. Considerable shear on the slitting punch should be avoided as it tends to put a

curl or twist in the tab which is difficult to remove. In follow-dies, if there is ample room it is usually best to pierce the pilot hole, if required, then slit around the tab in a second stage and finally bend in a third.

At *A* in Fig. 319 is shown the commonest design of tab. It is also the most subject to fatigue failure under severe strain. The straight cut runouts will often end with minute fractures starting in toward each other and offering a fine starting point for failure. Maximum stress is concentrated right along bend as the bending moment is greatest there and the thickness has been reduced by bending. The tab shown at *B* is relatively stronger in that the slitting runouts are directed outward and the width of metal under stress has been increased at the base compared with that in the body.

This principle was made use of, for a tab which had to be bent " in air," that is, using a bending punch only without the benefit of a supporting die underneath to govern the bending radius. When the design followed sketch *A* in Fig. 319 the bend was a sharp break and the corners were a distinct source of weakness. In redesigning, the body of the tab was actually reduced in width without damage. At the base the slitting cuts diverged at a 60° spread, so increasing the strength in proportion to the bending moment that the part bent naturally and freely to about a $\frac{1}{16}$-in. inside radius.

Sketches *C*, *D* and *E* illustrate the use of pierced holes or slots to make the corners of the bend more nearly fracture proof. In the first case simple round holes are used which unquestionably improve the strength of the bend but leave corners which may catch and prove objectionable. In the second case (*D*) the holes take the form of rectangles with three well-rounded corners. The fourth or sharp corner forms the runout for the slitting cut and leaves a barely noticeable step a few thousandths of an inch deep in each side of the tab.

At *E* is indicated a method similar to that shown in Fig. 318. Here a slot is pierced out all around the tab, insuring a good strong corner and avoiding the undercuts and corners of the other methods. The slot piercing punch is, of course, somewhat fragile. The width of slot should not be less than twice the metal thickness for most purposes.

It should be noted once more that, when metal is cold-rolled to the harder tempers, a tab bent across the " grain " or direction of rolling (*A*, *B*, *D*, *E* in Fig. 319) is much stronger and less likely to fracture than one having the axis of its bend with the grain as in Fig. 318 and at *C* in Fig. 319. The hardest practical rolled temper is, of course, desirable to give maximum stiffness and lightest gauge. A reasonable inside corner radius aids in avoiding fractures around the outer surface of the

bend. To get a full 90° bend provision must be made in most cases for some overbend to compensate for spring back of the metal.

Forming While Blanking.—Modern follow-dies offer means of completing more or less complicated parts from the coil in a single handling. Combinations of operations in such tools, which often bring together delicate cutting edges and unbalanced forming loads, have been made practical by the development of rugged " high-production " automatic presses. A device not commonly known but sometimes essential to complete a part at one handling is the combination of a forming operation into the final blanking stage by suitable grinding to shape of the cutting edges.

Forming to the shape of a blanking punch or die takes advantage of the high internal stresses created in the metal during shearing. It is naturally easiest to make a soft or annealed metal follow the shape of the punch. Metals which have been cold-rolled to hard or spring tempers will deflect to suit the tool, then spring back more or less toward their original condition. In such cases it becomes necessary to overbend, or to strike solidly at bottom stroke to set the metal. Striking bottom is usually out of the question in such dies, however, as the die is ordinarily open all the way through for discharge of the part.

An excellent example of this class of work is shown at the upper left corner in Fig. 320. The part is a camera spring finished complete from an extra-hard-temper brass in a follow-die. In order to avoid a complicated and frail punch in piercing around the ends of the part, the operation is divided into two steps, first piercing a plain slot at each end, and then piercing two adjoining slots at each end to match up with it. Two pilot holes are pierced in what is to become the scrap, also two crescent slots to outline a central pad. After an idle station the free ends of the blank are stamped to shape. Another idle station is allowed to permit the use of substantial shearing steels, and then the part is sheared out of the strip and pushed through the die to be discharged. In the course of this shearing out it is formed to the curved shape shown by the profile of the shearing punch. The punch is simple in section so that radius grinding of the profile in a suitable fixture becomes an easy matter. The radius on the punch is considerably less than that finally required on the part owing to the springiness of the metal. The dimensional tolerance on the arc for this piece need not be particularly close.

Again in Fig. 320, at the left center, the metal is made to follow the shape of the punch, but this time it is soft-temper (annealed) aluminum and does not spring away. A multiple progressive die first pierces and then forms and blanks 8 cupped washers per stroke at about 275 strokes

per minute. The blanking and forming operation is shown in section at *A* in Fig. 321. In some cases the centers of the blanks are not pierced out so that the only operation is the blanking and forming.

Fig. 320, upper right, shows the operations in the production of a special clevis. The point of particular interest is the combination of forming the two countersunk bevels while piercing the two hexagonal

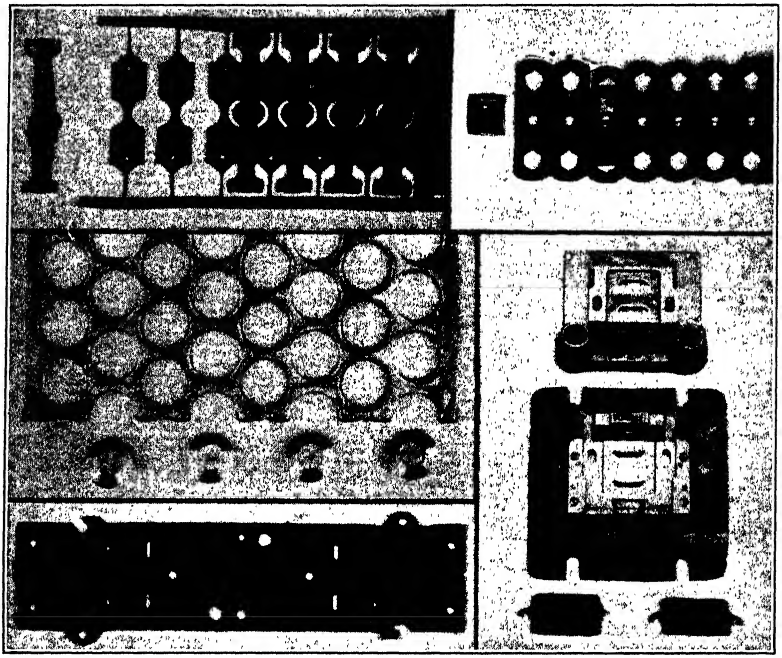


FIG. 320.—Upper left, follow-die operations in the production of a light gauge hard brass spring. The final curvature is formed by the punch in shearing out. Left center, heavy gauge aluminum cupped to shape as it is blanked. *See also* Fig. 321 *A*. At the upper right, in making a special steel clevis, hex holes are countersunk while being pierced. Lower left, conduit box parts in which the knockouts were slit with tapered punches to open up the holes for pushing the knockouts back flat. *See also* Fig. 321 *E*. Lower right, a combination die for slitting and forming louvres while stamping or forming a cover plate. Fig. 321 *G*.

holes. Straight hexagonal punches are used, ground flat for their cutting edges. The die is probably best made with two bushings having hexagonal openings and arranged as suggested at *B* in Fig. 321 so that they may be removed easily through the die shoe to be mounted in a revolving chuck for regrinding the bevel. In such a case the notching operation should be moved one station away to give space for the bush-

ings. The sequence of operations to complete the part is: pierce the center hole and two countersunk hex holes, notch, idle, form the spot-welding indents, idle, slit, flatten back, idle, shear off and bend.

At *C* in Fig. 321 is shown an operation having points in common with both those just described as both the punch and the die are formed. The object is to force most of the metal, which would normally be scrap from the hole, out into the wall of a flange or hub and then pinch off the small amount of scrap remaining. The method has been quite highly developed in the hot forging of the eye and the flange around it for pickaxes, hammers, and the like. It is also applicable to cold operations, especially in the softer metals.

At *D* in Fig. 321 is a compound piercing and blanking die arranged for producing the formed washer shown. Both punch and die are ground flat for cutting in the usual manner, and a thin removable plate is attached to the face of the lower die to take care of the forming. The formed piece is carried up in the punch to be stripped out near top stroke and discharged to the back of the press.

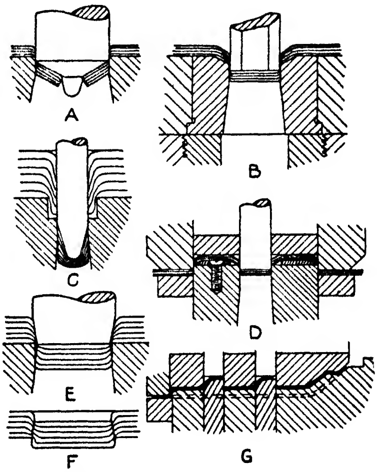


FIG. 321.—Several methods of forming while blanking or piercing, shown diagrammatically.

Fig. 320, lower left, shows a portion of an electrical conduit box prior to final bending operations. It is produced in the flat in a follow-die run in a "high-production" press: (1) pierce small holes, (2) slit knockout tabs and expand holes, (3) flatten back the knockout tabs, (4) blank. These operations may be separated if necessary for die strength. The interesting station is that in which the knockout tabs are slit, leaving them attached or tied at one point. The tie is left because of a slot milled down one side of the round piercing or slitting punches. These punches are tapered from the cutting edge up as shown at *E* in Fig. 321 in order to expand the surrounding metal so that the tab can be pushed back flush, and knocked out again at a later date with comparative ease. This would not be possible with ordinary piercing punches (as illustrated at *F*) since the slug and hole have different diameters controlled by the tool clearance. Care must be taken in designing tools with tapered punches (*E*), especially if they are to be used in springy or worn presses. Stops or contact blocks in the tools are usually required to prevent the

tapered punches from overtraveling and damaging the lower cutting edges.

One last example of combined cutting and forming is the production of ventilating louvres as illustrated by the small cover plate at *G* in Fig. 321 and in Figs. 320 and 322. Two steels set into the die shear and draw or form the metal into the louvres (Fig. 321 *G*). The blanks required are cut from scrap in a separate operation. They are then stacked in the magazine feed of the inclined "high-production" press shown in Fig. 322 and fed automatically into the die (Fig. 320) to be slit, formed and bent complete. The operating rate of 150 strokes

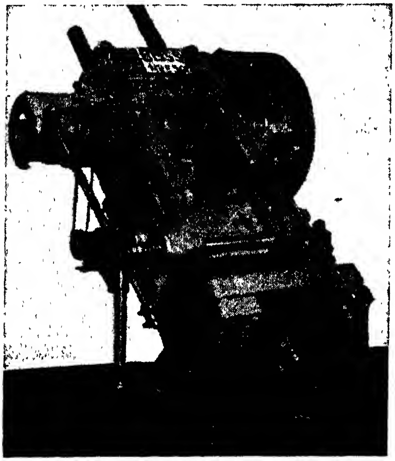


Fig. 322.—Inclined "high-production" press arranged with swinging magazine feed for the parts and die shown in the lower right corner of Fig. 320.

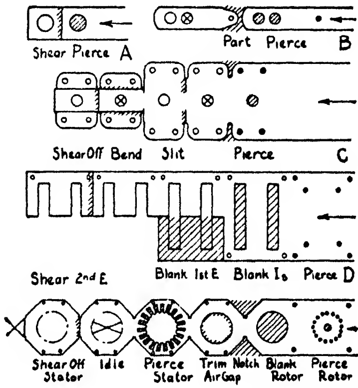


Fig. 323.—Typical "scrapless" layouts; *A*, *B* and *C* use coil stock; *D* and *E* are transformer and motor laminations from 8-ft. strips.

(pieces) per minute is maintained with the aid of an air jet to help in ejecting. The feed is arranged to take care of bowed, buckled or burred blanks and is so mounted that it is easily swung to one side for change of tools.

Economy of Metal.—The metal required for a stamped article is often the largest single item of its cost. The desirable policy is obviously so to plan the production of the part as to waste the least possible amount of metal. For small parts this is usually a question of strip or sheet layout, though it may sometimes be necessary to modify the design of the part or to insert additional equipment or operations in the production line up.

Scrap or waste metal is of little or no value, especially in the finely

divided state resulting from many press operations. Solutions have been: to bale strip scrap and fine perforations into a tangled bundle under hydraulic pressure, to rewind coil scrap into moderately dense coils or to pack shovel scrap in cheaply constructed light gauge black iron casks. In each case the effort is to get a better mass, which will melt rather than flash, and which will bring a higher scrap value.

Scrapless Layouts.—Absolutely scrapless layouts are extremely rare, because of the inevitable presence of pierced holes, notches, etc. The term is used rather to distinguish such arrangements as those shown in Fig 323 from those in Fig. 325 where there is a skeleton of scrap completely surrounding the product.

The absence of a supporting skeleton means that the strip must always be pushed rather than pulled through the die. The tail end of the strip is then either wasted or pushed through by hand, with a stick or with the end of the next strip. In automatic feeding the question of disposal of the tail end of the strip becomes important on account of the volume of material handled, and causes a sharp line to be drawn between the use of metal in strip or sheet form and in coil form.

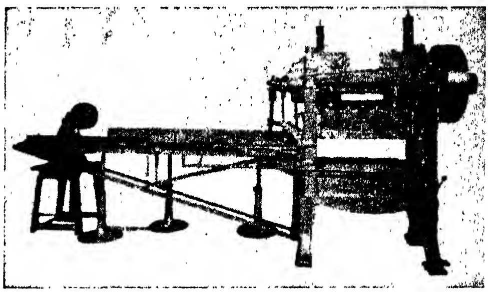


Fig. 324.—Automatic press with feed mechanism for producing laminations from strip stock without skeleton scrap.

Coils are usually relatively long so that ordinary or high-speed type single roll feeds can be used, with the loss of a relatively negligible piece of material at the end. Such feeds are illustrated in Figs. 309 and 317. Occasionally, if the material is relatively thick and the operation is simple and not fussy in point of accuracy, it is possible to butt the ends of the strip or coil and permit the roll to push the tail end of the last coil through by means of the beginning of the next one. Sketches *A*, *B* and *C* in Fig. 323 are typical of scrapless production from coil stock.

Sketches *D* and *E* in Fig. 323 illustrate respectively "scrapless" methods of producing radio transformer laminations and electric motor rotor and stator laminations. The material in each case is electric silicon steel, which, in the higher silicon contents, can be produced only in sheet form. This is because the metal strain-hardens at too rapid a rate for economical cold-rolling and must therefore be worked hot in packs of sheets thick enough to hold the heat. The sheets are slit up into

strips of proper width with lengths of about 8 or 10 ft. Economy requires that the sheets be fed right to the end and that they be started one after another without interrupting the machine or the flow of production.

Fig. 324 shows an automatic press for the scrapless conversion of transformer irons. It is equipped with a reciprocating finger feed which pushes the strip from the end until it has progressed far enough for another finger reciprocating between the last two stations of the die to pick up the feeding and continue it to the end of the strip. The latest developments of this type of equipment for high-speed operation are more compact and even more convenient for the rapid starting of the new strips.

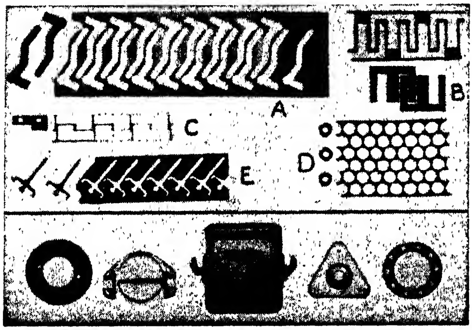


FIG. 325.—Above, typical skeleton scrap jobs illustrating especially the interlocking of various shapes. Below, parts made from scrap salvaged from other work.

The scrapless strip problem arises also in connection with some stretcher-leveled jobs and with tin-plate jobs. The former are handled as described above. Tin-plate strips, being short, are handled by the same push finger principles in automatic suction strip feed presses, Fig. 298.

Skeleton Layouts.—Fig. 325 is a collection of scrap skeletons to illustrate typical arrangements. The levers at *A* are blanked two at a time in a diagonal interlocked layout giving very good economy of material. The diagonal layout may not be practical if a hard-temper cold-rolled stock is being used and the layout brings a bend in the part at an unfavorable angle to the " grain " or directional properties (page 86) of the material. At *B* is shown one of many interlocked arrangements for transformer *E* laminations. The loss of metal is considerable compared with the design at *D* in Fig. 323. At *C* is a radius cornered nickel tag which must be blanked all around and which is planned to make very good use of the material.

At *D* in Fig. 325 is a typical diagonal layout for round work. The washers in this case are pierced and blanked six per stroke, the punches being located in the relative positions suggested by the cross-hatching, Fig. 299. The part at *E* does not lend itself to economy of material. For the limited production required, the diagonal placing shown is about the best, though something could be saved by using a wider strip and

passing through a second time to interlock a second row of blanks. In suitable automatic equipment this can be arranged but is not common and may prove troublesome.

Either strip or coil stock can be used up from end to end on any of the jobs shown in Fig. 325. High-speed double roll feeds are used in each case, and the entering rolls push the metal through until the outgoing rolls get a grip on the skeleton and finish the job.

In the use of tin-plate in sheet form, especially for the tops and bottoms of tin cans, the close-packed arrangements of blank, similar to Fig. 325 *D*, has been obtained by stagger feeding of the whole sheet. This was economical of material, but the equipments were either too slow or too complicated to survive. The trade therefore continued to

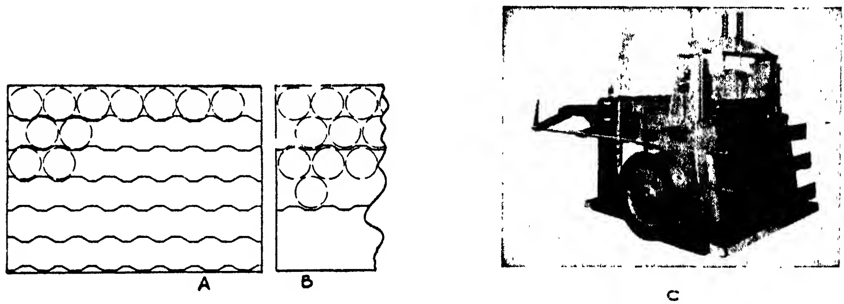


FIG. 326.—Tin-plate sheets scroll sheared for economy preparatory to automatic handling in single- or double-die suction strip feed presses. Right, an automatic scroll shear which trims tin-plate, cuts it up according to *A* or *B*, and sorts the strips as required.

slit the sheets into straight strips and feed these in strip feed presses, until the development of the scroll shear. This machine, as shown at the right in Fig. 326, is arranged to trim the ends of sheet and then cut it up into a series of scroll strips to achieve nearly the economy of the stagger layout. Thus single row scroll slitting, Fig. 326 *A*, usually saves about 5 or 6 per cent of the material expense compared with straight strips. The two-row arrangement for double die strip feed presses may save up to 6 or 8 per cent on the material according to size and layout, Fig. 326 *B*.

Separate Blanks.—Another expedient for economy in material costs is to buy ready-cut blanks to size from the mills. This saves shipping charges on the scrap and puts the salvage of the scrap directly in the hands of the mills. It is a practice which is becoming increasingly popular though limited perhaps to fairly steady production requirements.

Alternative to that, Fig. 327 shows at the left a type of press, built for the manufacture of small motors, for cutting up whole sheets of silicon steel into stator size discs, following the closely packed staggered arrangement of Fig. 325 *D*. The economy of material in this case is often 12 to 15 per cent compared to the straight strip method.

In either of these cases the prepared blanks must be fed to succeeding operations either by hand or by an automatic magazine feed. Fig. 327, at the right, shows such a feed attached to a standard inclinable press.

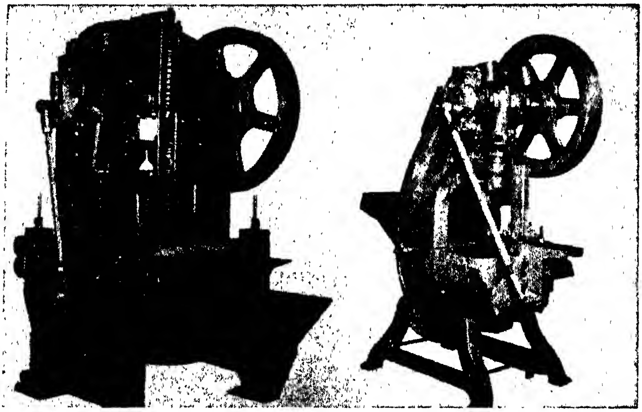


Fig. 327.—Left, an automatic press for cutting up full-size sheets of silicon steel into blanks for motor laminations with maximum economy of material. At the right, a simple adjustable magazine feed for handling separate blanks, either plain or slightly formed, for subsequent operations.

Others on multiple-slide and high-production presses are shown in Figs. 322, 347 and 348.

Scrap Salvage.—In many cases scrap unavoidably produced in making large stampings may be used up for smaller parts. Thus automobile manufacturers use up the scrap blanked from window openings of body stampings. The steel companies turn pipe skelp ends into washers in the same way.

Automatic equipment can be used in some cases for the latter job. In general, scrap salvage requires considerable untangling, sorting and handling and finally hand feeding for the press operation. Even so, the use of scrap is worked out satisfactorily in many cases. Fig. 325 shows at the bottom a collection of parts produced from blanks cut from scrap in hand-fed presses. These blanks were then handled at 125 to 150 SPM in a magazine-fed press for the final processing.

Gauge Reduction.—In the initial design of the stamping, except for deep drawing, it is often possible to save by using metal strain-hardened by rolling to half hard or hard temper. This may permit a reduction of 20 or 30 per cent in gauge with a proportionate saving in cost. In doing so, of course, the designer must take care not to have sharp bends, especially parallel to the grain. Judiciously placed reenforcing beads and flanges also contribute to the successful use of the lighter gauges.

Bending in Follow-Dies.—A great many follow-dies involve one or more bending operations, usually in combination with piercing, notching, parting, shearing and/or blanking operations. It has been pointed out that coil stock with its harder tempers has distinct directional properties which must often be considered in bending.

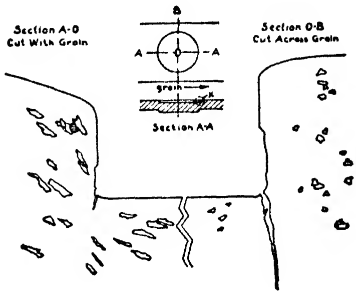


FIG. 328.—Differences in directional properties of quarter hard bronze strip. Traced from photomicrographs of right-angle sections through a partly sheared sample.

A visual illustration of this directional difference is found in Fig. 328. Inset in the upper center is a plan and section sketch to illustrate the method of the experiment. A strip of quarter-inch thick bronze rolled to about quarter hard temper was placed in a round blanking die in a testing machine. Pressure was applied until the beam dropped just as the fracture started. The sample was then cut in quarters along the center lines, and the edges were polished and etched. Fig. 25 *A* shows a photomicrograph taken at the point marked by the circle and the letter *X*. This was etched to show the flow of the metal under the pressure of (the corner of) the blanking punch.

Two other micros, Fig. 25 *B* and *C*, were taken at similar points along the section *AO*, which was cut with the grain of the metal, and the section *OB*, cut across the grain. These were etched to bring out metal structure, and tracings of them showing a few typical grain outlines are reproduced in Fig. 328. Note that the grains were considerably elongated in the direction of rolling as is seen by a comparison of their side and end elevations. Note, in comparing the two sections, that the upper edge of the metal was carried much farther down before the fracture occurred in section *AO* than in section *OB*. That is, the metal showed the greatest plasticity where the line of the shear cut crossed the grain of the metal. When the shear cut is parallel to the grain the metal evidenced greater hardness or resistance to deformation and the fracture started more quickly.

The difference in the directional properties of cold-rolled metal was illustrated well in Table X *A*. This table noted that the bend test for quarter hard (low-carbon) steel should show that the metal could be doubled back upon itself in the direction of the grain without fracturing around the outside of the bend; but across the grain it should not be expected to make more than a 90° sharp bend without a fracture.

Figs. 329 to 331 illustrate progressive die operations arranged in order of the severity of the bending strains imposed upon the metal. In Fig. 329 coil stock is fed to a stop and is progressively indented, pierced, parted and bent, after which the finished piece is stripped clear of the punch and the die and then blown out of the way. A fair metal thickness and accompanying clearance between cutting edges is desirable because the parting punch must enter the die a considerable distance. This is so that the blank will be free to bend up as the forming punch strikes it. The bend in this case is the easiest possible type, being across the grain and having a large radius. Metal which has been severely strain-hardened by rolling to the higher tempers should be satisfactory for this part.

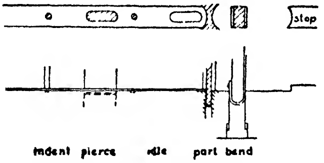


FIG. 329.—An easy U bend across the grain. A simple follow-die, feeding automatically to a stop.

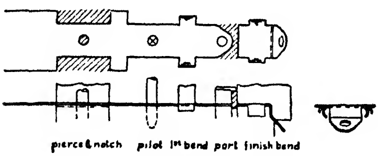


FIG. 330.—A rather fussy part, including an undercut bend, as produced complete in a follow die, without loss of control.

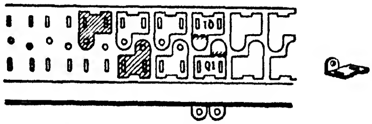


FIG. 331.—A follow-die sequence for the production of two angle brackets per stroke at a fast operating speed.

Fig. 330 shows another part produced from the coil in a single roll feed automatic press. The operations are pierce and notch, pilot, bend the outer portion of the curl, part, finish bend the curl and make the two bends in the free end. Note that in this case it is not desirable to have the piercing punch enter very far as the bends should be nearly completed before the part is separated from the coil. The pilot and spring stripper are therefore able to prevent creeping of the stock in making the 90° bend. This sharp bend is across the grain of the coil, taking advantage of the greatest ductility of the metal, and the curl which runs with the

grain is so easy a radius that a fairly hard temper may be used for this part, probably one step softer than that for Fig. 329.

The part shown in Fig. 331 would be produced from coil stock in a double roll feed press with a scrap cutter. The operations are, first, pierce the holes, then pilot, then blank out and return to the stock using a spring stripper and a spring pad in the die, then strike back tight in the scrap, then bend the tabs and strike the lettering, then push out the

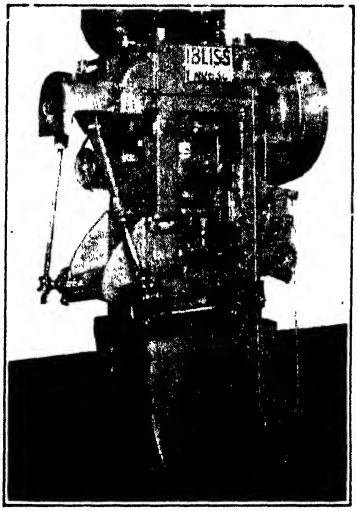


FIG. 332. — A "high-production" press with single roll feed and a push-over motion for a secondary bending operation.

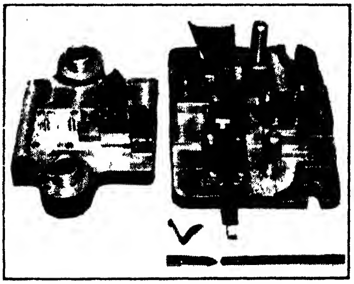


FIG. 333.—The tool used in the press in Fig. 332 to pierce, bend and part, push over and finish bend at about 200 SPM.

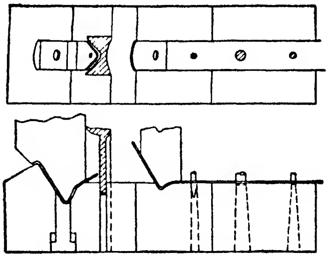


FIG. 334.—An alternative method of producing the same part as in Fig. 333 without the use of the push-over slide.

finished parts usually using spring pins in the punches to help clear the pieces if the speed is high. As the angle of the shear cut, due to clearance, makes it practically impossible to push a blank back through its own scrap, the operation must be laid out so that the blanking, bending and pushout are in the same direction. As the tabs in this case are in the direction of feeding and there are no obstructions to interfere with grooving the die from the bending station to the pushout position, this job may be run without lifting the strip, which is a desirable feature for

speed. In $\frac{1}{32}$-in. steel this part can be produced at 300 SPM or better. In a push-back operation a rigid press is essential, and if the metal is thin stops may be required in the tools to insure coming to the same point every time. A sharp right-angle bend laid out with grain of the metal for scrap economy and production efficiency makes it necessary to use metal of a softer temper here than in the previous case.

Figs. 332 and 333 show the press and die for the production of a part made from sixteen gauge (0.0625-in.) coil steel, in which a transfer operation is involved. The strip and samples in Fig. 333 are laid in the same relative positions that they occupy in die and in the press. In the first step two holes are pierced. In the next, the end of the blank is bent down and a parting punch separates it from the strip. The blank is then pushed back to a final forming station by a spring finger and reciprocating slide which is actuated through a bell crank from a cam on the end of the press crankshaft. Aside from this the press is a standard " high-production " unit with single roll feed. In point of severity this job rates with Fig. 330 in having right-angle bends across the grain.

By way of speculation it seems possible that this part might also have been produced without the push-over mechanism as suggested in Fig. 334. This scheme is based upon letting the parting punch enter deeply to free the ends for bending just as the bending punches make contact. The preliminary bending gets the long leg up in position for the final bend. The operations then are pierce, pilot and prebend, part and final bend ejecting to the back. The press stroke must be somewhat longer in this case than in Fig. 332, and one bending radius must be refinished each time the cutting edges are shimmed up and reground. A substantial spring backed pad should be furnished to prevent creeping in the final bend. A spring stripper at the piercing station and entering guides for the stock would, of course, be required.

Drawing in Automatic Equipment.—Drawing operations can be performed automatically in so many different ways with so many points of relative merit that it does not seem wise to limit this part of the discussion to follow-dies alone. Combination dies for both single- and double-action automatic presses frequently have advantages in scrap economy and simplicity, for single operation draws, though they may require special press arrangements for maximum speed. Follow-dies of different types and a dial or transfer feed sequence of separate dies each have their relative merits.

Combination Dies.—Combination dies for blanking and drawing one or more shells per stroke are common and well known. When used in automatic equipments such dies are usually of the inverted type shown

in Figs. 162 and 168 and are used in single-action presses equipped with pneumatic or other drawing attachments.

It is often possible to arrange combination dies to include a piercing or a stamping operation on the bottom of the shell. In any case the shell is lifted in the punch and stripped out toward top stroke to be discharged above the surface of the die. An air jet, a reciprocating tray or a swinging finger may be used to remove the shell, but more often the press is inclined and gravity is employed, with the aid of an air jet if the operating speed is high.

Thus Fig. 335 shows an automatic " high-production " press mounted on inclined legs to be equipped with a double combination die for blanking, drawing and piercing two shells per stroke. The die is so laid out that the two rows of blanks are interlocked on the (coil) stock with attendant scrap economy. Even in single rows combination dies are usually more economical in the matter of scrap than follow-dies, but of course at a sacrifice of some speed in most cases. Piloting of the metal is usually unnecessary with an accurate automatic feed, and roll straighteners built into and driven with the feed may be used if required.

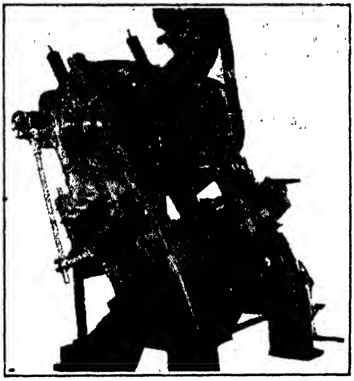


Fig. 335.—A "high-production" press (Bliss No. 675), inclined and arranged for the automatic production of drawn and pierced shells two per stroke from coil stock.

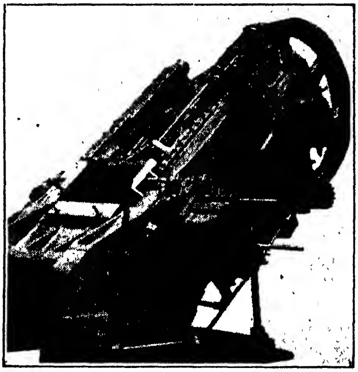


Fig. 336.—A 9-in. stroke press with slow-draw quick-return drive, high speed feeds and straightener, etc., for producing 150 drawn shells per minute. Coils weigh nearly a ton.

The slow-draw quick-return drive shown in Fig. 336, and described in connection with Fig. 261, has considerable advantages for automatic equipments on the drawing of steel. It increases materially the press operating speed and production without increasing the drawing speed or

the tendency to pick-up or score. The unit shown is equipped with high-speed double roll feeds and straightener for handling fairly heavy coil stock up to 24-in. wide and with combination blanking and drawing dies for producing three odd-shaped shells per stroke. Air cushions are adjustably arranged in the bed.

Follow-Dies.—Drawing operations in follow-dies may be grouped according to three general methods of taking care of the movement of the metal and reduction of the projected area of the blank. Obviously the center distance between each of the operations in the die must remain substantially constant. Accordingly all the metal required for the drawn shell must be gathered in the first station or a relief must be

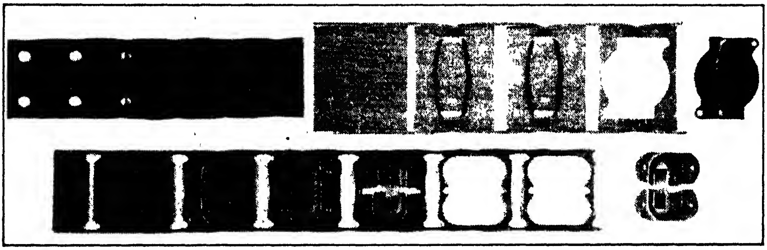


FIG. 337.—Strips showing typical sequence of operations in follow-dies. *A* (upper left): 0.008-in. copper, no relief, 250 SPM. *B* (across bottom): 0.085-in. steel pierced relief 165 SPM. *C* (upper right): 0.018-in. C.R.S. with slit relief to save metal between blanks.

cut between blanks so that drawing at one station has practically no effect upon the operation at the next station.

Figs. 174*A* and 338*A* illustrate methods of producing radiator fins for assembly on the tubes of heating and cooling units. In both cases buttons are drawn up in the first station of sufficient size to provide the metal necessary for the final flange. This metal is obtained partly by stretching but to a greater extent by drawing in from the sides and from the free end of the strip. The second station in both cases is idle, the button being held under spring pressure to anchor the strip and prevent metal being drawn from that side into the first station. Sketch *A* (Fig. 338) shows the method followed in the equipment in Fig. 339. The third and fourth stations reduce the diameter of the original button. In the fifth the bottom is pierced out; and in the sixth the edge is burred down to increase the height of the shell, the corner radius is stamped sharper and the flange is flattened.

The machine for this job, shown in Fig. 339, is a standard " high-production " press with high-speed double roll feed and a special shear

blade operated through a ratchet mechanism which counts off any desired number of pitch lengths from one to fifteen before operating. Thus

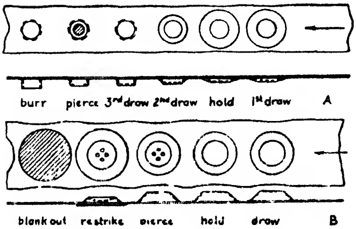


Fig. 338 *A*.—Sequence of operations used in Fig. 339, no relief. Metal gathered from sides and free end. *B*. Follow-die job in 0.025-in. C.R.S. Sufficient metal gathered in first station for final reforming operation.

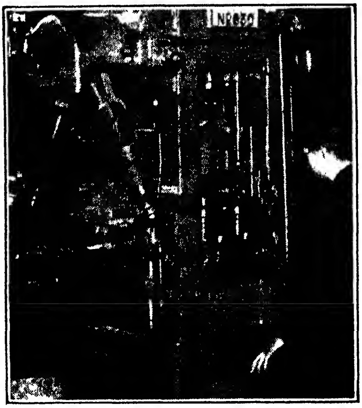


Fig. 339.—A "high-production" press producing aluminum radiation fin at 300 SPM with timed shear to cut off predetermined lengths.

the length of the finished fin may be controlled to suit the length of the finished radiator. This equipment operates at 300 SPM feeding one pitch length per stroke. It can produce two or three rows of buttons from wider stock in the same manner as the single row shown.

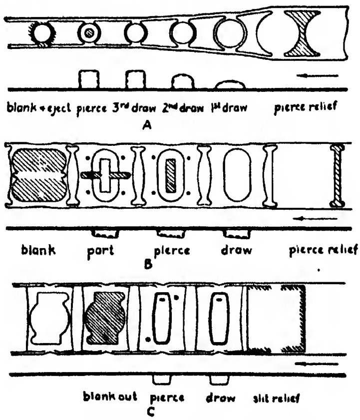


Fig. 340.—Three follow-die strip layouts showing methods of piercing or slitting for drawing relief in which the strip width is reduced.

Fig. 338 *B* shows a job somewhat similar in type in that the necessary metal is gathered in the first station from the sides and the free end of the strip. The second station again serves for holding purposes. The part is finished up in the next two steps, piercing the central holes and drawing the dish and the edge bead from an excess height of metal in the side wall. The part is blanked out in completed form in the fifth station.

The second and perhaps the commonest type of follow-die work involving drawing operations is illustrated at *B* and *C* in Fig. 337 and in

Fig. 340. In this case clearance is pierced or slit between blanks to permit the metal to be drawn in lengthwise without bothering the center distance. The blanks remain attached to strips of scrap along each edge, and as the blank is drawn the strips of scrap are pulled closer together.

The same job, an automobile door latch part, has been shown at *B* in Fig. 337, at *B* in Fig. 340 and in Figs. 341 and 342 to give a complete story. The metal was 0.085-in. drawing steel in coils, and the job was run at 165 SPM, producing a right- and a left-hand part each stroke.

The first operation was to pierce a clearance slot having a width a little under twice the metal thickness. The part was drawn to its full

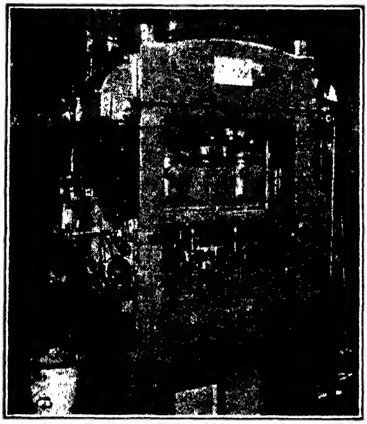


Fig. 341.—The "high-production" press operated at 165 SPM to produce the job shown at *B* in Figs. 337 and 340.

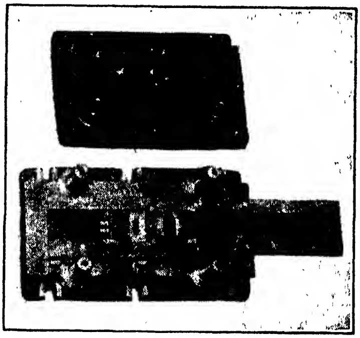


Fig. 342.—Follow-die built of high-chrome high-carbon steel to produce the job shown at *B* in Figs. 337 and 340.

depth in the next step, using heavy springs back of the stripper plate for partial blank holding. The third station is for piercing and the fourth for cutting a parting slot following the profile of the piece. In the fifth station the two parts are blanked out and may be kept separate as they fall.

The die for this part, shown in Fig. 342, is built of high-chrome high-carbon steel substantially mounted in a standard four-pin die set. It is provided with the usual entering guide, fixed side guides and spring stripper. The press which is shown in Fig. 341 is a regular "high-production" press with double roll feed, starting gauge, stock oiler and scrap shear.

Fig. 340 *A* shows a simple round shell drawn in two steps with pierced clearance to permit the metal to move in. The job shown in Figs. 337 *C*

and 340 *C* employs a slitting operation to free the rectangular blank at all but two points in the center of each side. The slitting eliminates scrap loss between blanks. The amount which the drawing operation

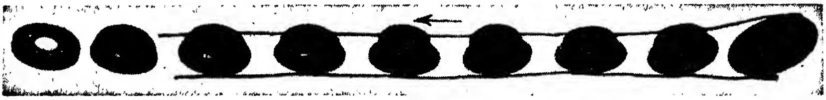


FIG. 343.—The progressive die operations in the production of a shell for a V-belt pulley.

pulls the metal in is quite clearly shown in the photograph. The job in this case is drawn down and blanked down through the die. In Fig. 340 *A*, it is drawn up, which has some advantages in point of blank-holding but may be inconvenient with respect to blanking out and to maintaining a feed level. The direction of the draw must be left to the preference of the designer and the details of the specific job.

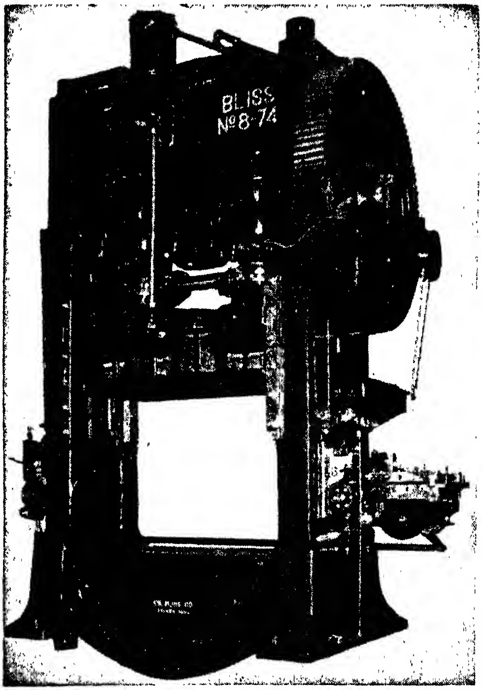


FIG. 344.—The automatic press for the job shown in Fig. 343.

Figs. 343 and 344 illustrate the method and equipment for the production of a V-belt pulley. The sample strip has been detached from the coil right through the clearance space pierced between successive blanks to give the metal freedom to draw in. The original pierced opening allowed nearly ⅛-in. clearance between blanks, and of course this opens up considerably as drawing progresses since the shell is drawn quite deep.

The operations are, in order: pierce between blanks; draw; redraw; redraw; restrike to square up draw radius and to flatten flange; rubber bulge using rubber punch and wedge action split die to close around the shell during the

bulging; idle; blank through (scrap not shown). Subsequently the part is restruck in a separate operation and then pierced.

The press, Fig. 344, is 74 in. wide and has a 12-in. stroke. The feed timing is so arranged that feeding is completed in the top quarter of the stroke, leaving 9 in. for draw and liftout with proper clearance and indicating about 4-in. maximum shell depth. Coil material up to 15 in. wide is fed through the press housings, with provision for roll feeding, straightening and scrap cutting. Ordinarily, when progressive dies are used, straighteners should be mounted away from the machine with a controlled slack loop between them and the feed to permit releasing the

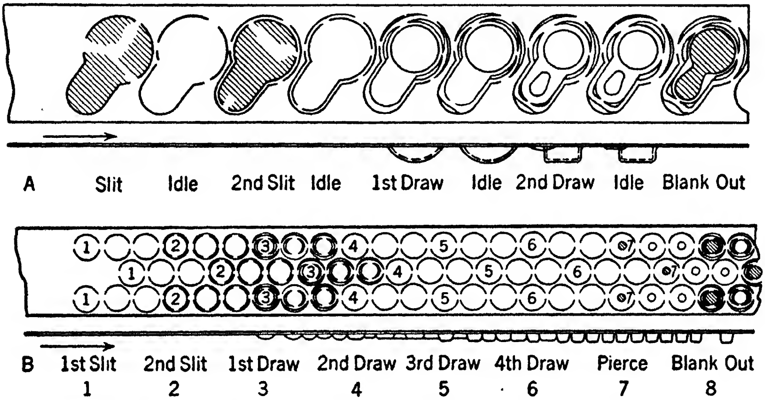


Fig. 345 *A*.—Steps in the production of a drawn cap in the follow-die, Fig. 346. At *B*, the layout of a multiple follow-die for producing three cartridge primer caps per stroke.

feed rolls for proper piloting. Extra die space is furnished to take care of Marquette blank-holding cushions above the punch plate.

Another type of follow-dies for drawing operations is illustrated in Figs. 345 and 346, in which the relief to permit metal to be drawn into the cup is provided by slitting two concentric ring cuts leaving a ring of scrap. This ring is attached both to the blank and to the main skeleton of scrap at two, three or four points so alternated that the blank can be drawn in freely and yet be kept tied firmly to the skeleton.

The scrap skeleton can be fairly substantial, and owing to its freedom from distorting strains it gives this method certain advantages over the two previously described for complicated dies and for multiple follow-dies. There is usually a somewhat greater scrap loss to be taken into account, however.

Fig. 345 shows at *A* the details of the operations performed in the die shown in Fig. 346. There are idle positions following each of the

working stations in order to give ample strength in the die and room for renewable bushings wherever required. Although this practice is very desirable where it works out well, it is possible to get into trouble by spreading a die out too long, owing to curvature of the strip or non-uniform properties of metal throwing the last operation out of proper alignment with the first.

In the first station in Fig. 345 *A* an outline is slit which is a little larger than the desired blank all around. The second station is idle, and in the third the actual outline of the blank is slit inside of the previous cut. As shown in Fig. 346, three slots each are milled into the punches for these two operations so that the slitting cuts are interrupted at the corresponding points. These tie points are spaced 120° apart, and one group is rotated 60° from the other group. This permits the blank to

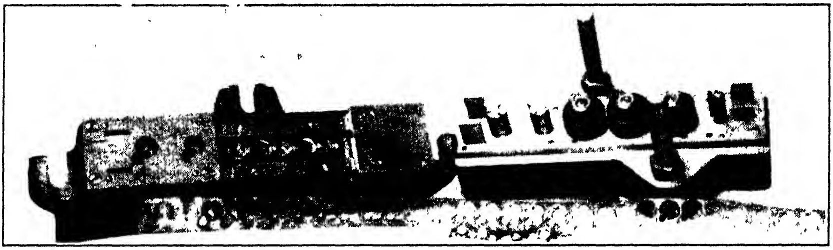


FIG. 346.—A follow-die employing the double slit ring method of freeing a blank for a drawn cap.

be drawn in at the fifth and seventh stations without getting out of control and without distortion to the outer scrap skeleton. In the last station the finished cap is blanked out all around and pushed through the die. In the actual die, Fig. 346, a third draw or restriking station is furnished which is not shown in the sketch.

Four spacing or distance blocks are furnished at the four corners of the punch to contact with the die and prevent the slitting and drawing punches from entering too deeply. This is a very important point in many delicate dies of the follow type. Such spacers also minimize tipping of long dies when loads are unbalanced. Note, in Fig. 346, that solid fixed strippers are used for the cutting stations, while the spring-actuated blank-holding rings serve to strip the drawing punches.

Fig. 345 *B* shows the sequence of operations in a foreign multiple follow-die for the production of small percussion cap ferrules. Here two slit circles each with two interruptions in them are used to free the blanks so that three sets of drawing operations may proceed at the same time in the same skeleton without interfering with each other. Two

idle stations are required between each set of working stations in order to give room for die bushings and sufficient strength. The operations are, in order: first, slit the outer circles with two interruptions at points paralleling the axis of the strip; second, slit the inner circles with two interruptions at points perpendicular to the axis of the strip; next the blanks are cupped, after which come three redrawing operations; then

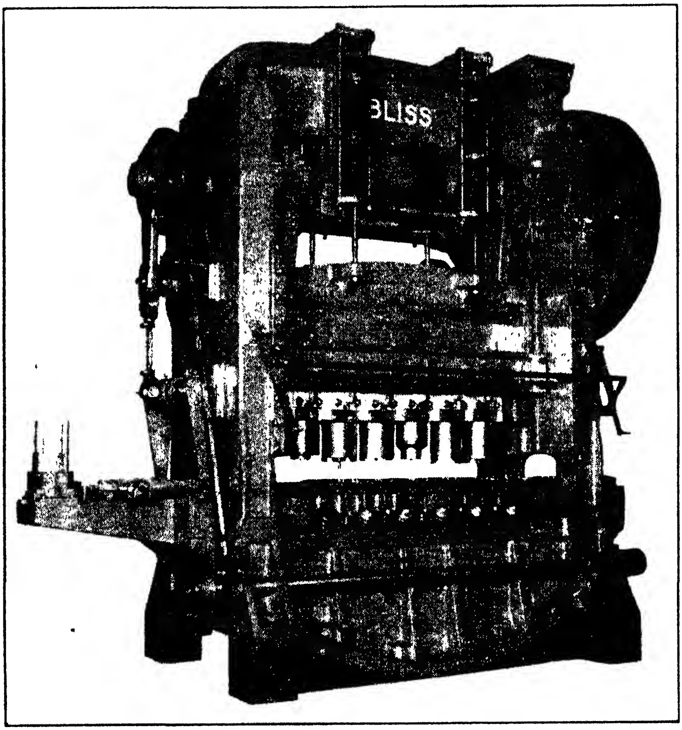


FIG. 347.—A 7-in.-shaft, 96-in. wide multiple slide press of the straight-sided type, for a series of six operations from a flat blank to a drawn and trimmed shell of odd contour.

piercing a small hole in the center of the bottoms; and finally blanking out the finished primer cups.

Multiple Operation Equipment.—In many series of drawing and accessory operations for one reason or another the stampings cannot be kept attached to each other or to a skeleton of scrap, and must therefore be moved separately across a series of separate dies. For such work, presses have been developed equipped with transfer feeds and known as multiple slide presses, Fig. 347. The name comes from the common use

of a small slide built into the main slide for each operation in order to provide an individual adjustment for each set of tools. This feature is usually of extreme importance for convenience in tool maintenance. It is also common to furnish a cam-actuated knockout mechanism in each slide in order to strip the work positively from each punch, and in proper time relationship with the feed.

The means of moving the stamping from die to die across the press usually involves the use of a set of reciprocating feed bars with a transverse opening and closing motion normal to the direction of feed, to positively grip and release each stamping. In connection with this feed it is usually necessary to have shells or parts with a flange or square edge to slide upon and a sufficiently large area of base in proportion to height to stand in stable equilibrium. Accordingly shells are most commonly

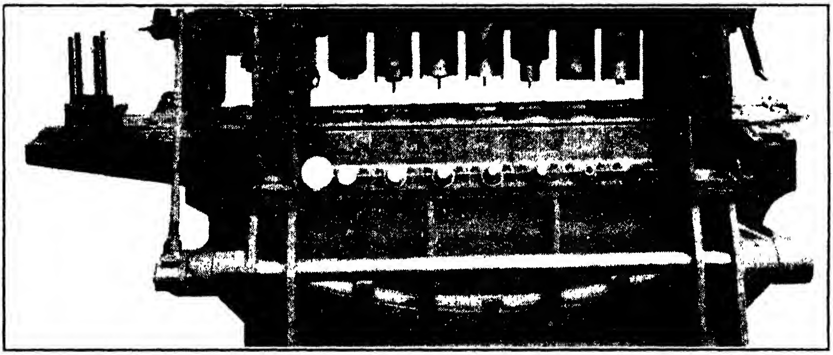


Fig. 348.—Close-up of tools, transfer bars, magazine feed and operations in a seven-station, 72-in. wide multiple slide press.

handled with the bottom up and are drawn down over inverted plugs with blank-holding attachments in the bed of the press.

An example of this practice is shown in Fig. 348. Here a blank, which is brought into the first die from a magazine, undergoes four successive drawing operations. The large diameter is trimmed in the fifth step and burred down in the sixth to give a square edge for flash welding. The small end is pierced in the sixth and burred up in the seventh die to increase the height and give a square edge.

For the sake of scrap economy the blanks were cut from coil stock in a multiple die, two or three per stroke in a roll-fed high-production press. An extra drawing operation was introduced to reduce the strain on the metal per operation and thereby reduce the possibility of breakage. The equipment replaced six hand-fed presses with their operators and with helpers for moving work in process. It saved a very considerable

amount of space, increased production to a constant rate of 25 pieces per minute and reduced the work-in-process inventory to a minimum.

An alternative method for parts which, owing perhaps to an irregular edge, must be drawn open side up, is the use of a double-action toggle press. Such a machine is illustrated in Fig. 349. It is arranged for five working stations and provided with a transfer feed and a friction dial feed for introducing a previously blanked and drawn shell. Separate

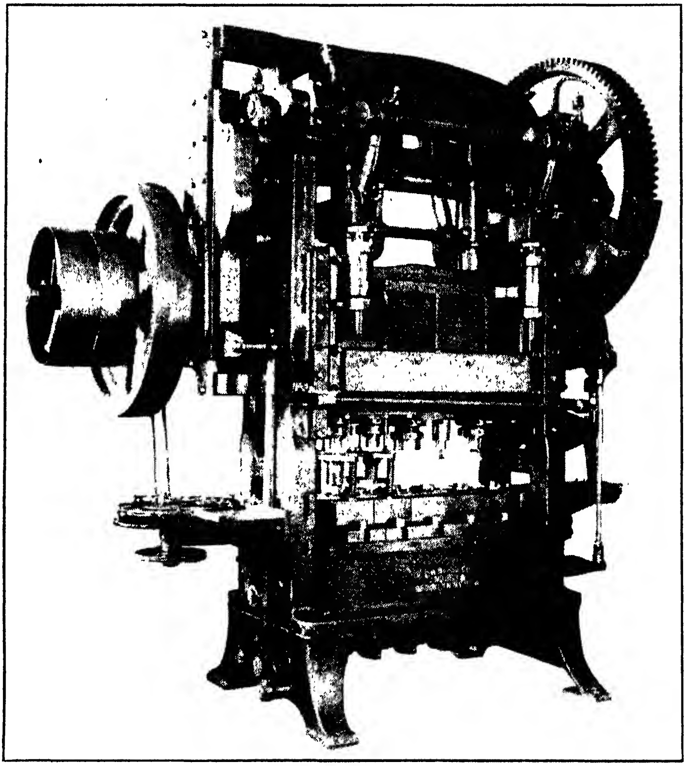


FIG. 349.—Shells, fed open side up by friction dial and transfer feeds, are subject to five operations in this double-action toggle press.

adjustments are built into each set of punches in this press. This is obviously not so satisfactory as the practice of building the separate adjustments into the press slide once and for all.

Fig. 350 shows several typical series of operations performed in multiple slide presses. The asterisks indicate cases in which a previously blanked and drawn shell was fed, usually by friction dial, to the first station of the presses. In other cases, as at E and G, coil stock was fed

across the first station by means of a single or double roll feed and the blank was cut or cut and drawn before passing on to the subsequent stations.

At *A* in Fig. 350 are shown two series of shells each produced in a five slide transfer feed press with an anneal between the two series. Such shells may also be handled in grip fingers mounted in an inner slide which is mounted in turn in a transversely reciprocating outer slide. A lag in the travel of the inner slide relative to the outer one, due to friction, causes the grip fingers to open and close at the extremes of travel.

In still another method the fingers are spring-actuated to snap onto and off from the shells. The feed slide must then be so timed relative to the drawing punches that the latter will act to hold and release the shells

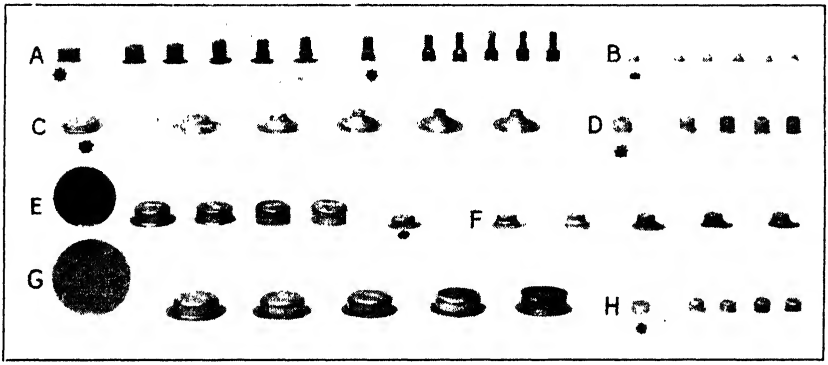


FIG. 350.—Eight typical series of operations performed in multiple slide presses with friction dial feeds (asterisk), or roll feeds serving the first station.

from the spring fingers. This method is more often applied to single-action reductions in which the shells are handled open end up and would be in some danger of falling over.

Reducing operations in which the shell can be pushed through the die may be handled as in Fig. 351 by stepping down from one level to another in each reduction and then pushing across to the next die with a simple push-over slide. This particular example is of double-action work and involves only two operations. The same principles, however, may be applied to single-action reductions and a greater number of stations.

At *B* in Fig. 350 are shown operations in the production of a coffee pot cover knob. At *C* are the steps in making a "harness oil can" breast, including trimming and piercing. At *F* is the sequence in making a 5-gal. oil can nozzle. The nozzle is an offside shape which must

be kept twisted around the right way while in transit across the several operations. This is done by properly shaping the gripping fingers. At *G*, after blanking, drawing and restriking, the outside edge is trimmed, the center is blanked out and the side wall is then burred up to get a maximum of height from a given blank.

Dial Feeds.—The last of the methods mentioned for performing a series of drawing group operations automatically is illustrated in Fig. 352.

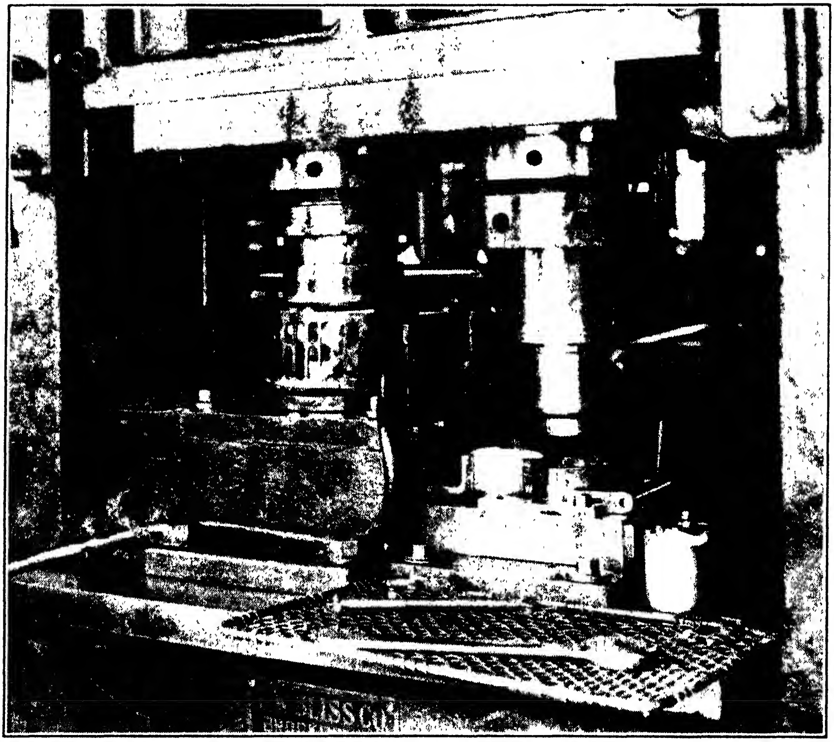


FIG. 351.—A double-action press job illustrating the method of push-through dies and push-over feeds for a suitable series of operations.

As shown, it is based upon the use of several stations in a ratchet dial feed. Previously formed shells are fed by hand or from a hopper into one of the forward stations of the dial. The shell is then carried around to the back and through the successive working stations. It may be pushed through in the last of these or carried farther and picked out automatically.

Dial feeds are extensively used in single step, second operation work, but only in comparatively few favorable applications for progressive

jobs. Three limitations account for this. All punches are carried in one holder on the slide, and separate adjustments are usually required in each punch. This is fairly easy for simple round drawing punches. For most operations in series, the dies must be grouped under the dial where

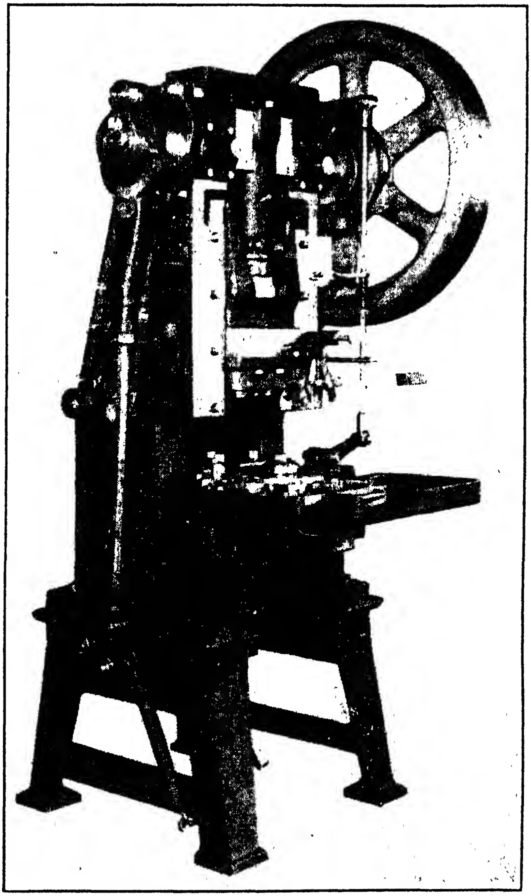


FIG. 352.—A five-operation ratchet dial feed reducing press for ironing, reducing and pointing bullet jackets.

they are less accessible than in transfer feed or roll feed equipments already discussed. The process is usually limited to cylindrical-shaped or flanged parts having a (practically) constant outside diameter during the series of operations so that the dial bushing can maintain each part in a central location at each station. Adjusting or centralizing bushings

have been built for shapes which change during the process, but such cases are more easily cared for in the transfer feed type of equipment.

The press shown in Fig. 352 represents a type which is quite popular for a number of operations in the production of small arms ammunition. These include particularly pointing of the bullet cases, necking the cartridge shell (done above the dial) and some of the ironing operations.

The machine is a very shallow throat C-frame reducing press with long stroke and long gibs. It has a cam-actuated bottom knockout, cam-driven ratchet dial feed with sixteen stations, automatic safety lock,

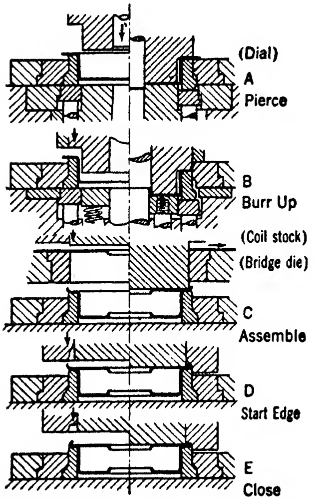


Fig. 353.—Five working stations for the dial feed unit in Fig. 354. Punch shown with stroke partly up at the left and down at the right.

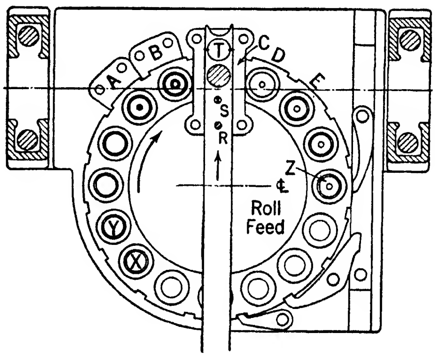


Fig. 354.—Combination of single roll feed and ratchet dial feed. Straight-sided double-crank press selected for convenience and tool life.

pick-off attachment, fixed stripper and a punch-holder arranged for five operations. A suitable hopper may be mounted on the bracket on the top of the press.

Figs. 353 and 354 are arranged to show a series of operations in a dial feed, and the use of an auxiliary roll feed. Fig. 355 shows another such combination of dial feed and roll feed on a small inclinable press.

In Fig. 353 are shown in section the five working stations of the dial feed. A composite dial bushing is used, made up of an outer ring which is fixed in the dial and an inner ring which is free to float. In each case the punch is shown approaching the die at the left of the center line, and in its bottom stroke position at the right. A shell, which has been pre-

viously blanked and drawn in a combination die served by a roll feed, is placed in the dial at either of the loading stations (X- Y, Fig. 354).

Coil stock is fed across the dial by means of a single roll feed in the center. This stock is pushed across a bridge type follow-die to produce the part which is to be assembled with the drawn shell. The operations

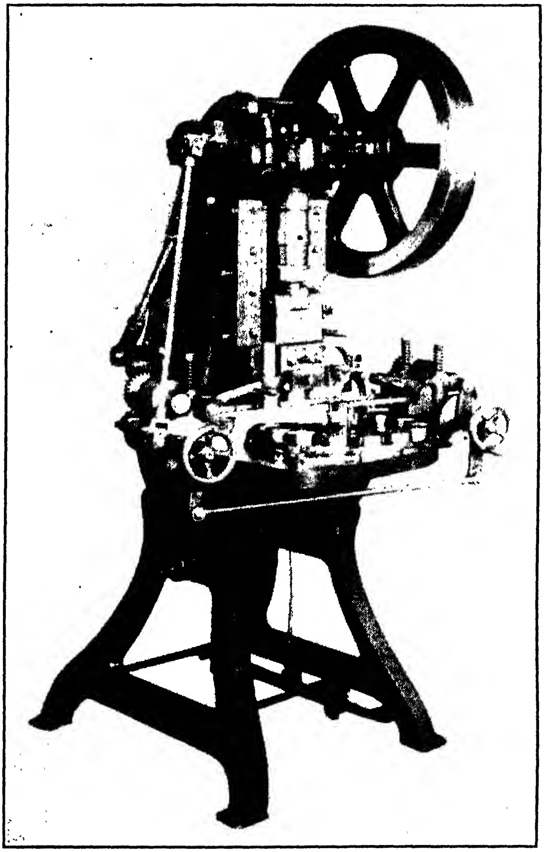


Fig. 355.—A C-frame press with roll feed for strip material and dial feed for drawn parts, for a series of operations.

in the follow die are: pierce a center hole (R), pilot in it and burr it down (S), blank out a disc and push it through into the shell (C) and finally cut up the scrap (T), which slides away to the back.

The operations in the dial are: first pierce a hole in the bottom of the shell (A), then draw up a burr around the outside edge and around the center hole (B), next blank into place the second part from the coil stock

(*C*), then start to bend in the outer flange (*D*) and finally close the outer edge (*E*), completing the assembly of the two parts. At the station (*Z*) the parts are picked off and ejected to a chute at the side.

It will be noted that the press indicated in Fig. 354 is of the straight-sided double-crank class like that shown in Fig. 356 rather than the inclinable C-frame type, Fig. 355, which used to be employed exclusively.

Whenever a dial feed or a combination of feeds may be required, the work is certainly in the quantity-production class and tool life becomes worthy of consideration. This is especially true when operations are grouped and feeds become complicated so that every shutdown for tool

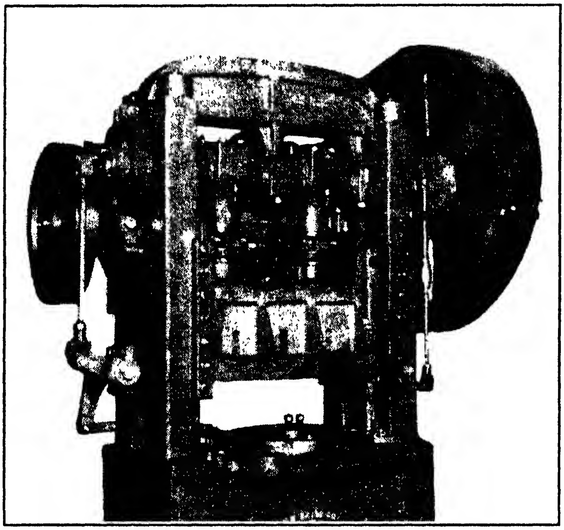


FIG. 356.—A ratchet dial feed in a double-crank straight-sided press, showing that working stations are accessible from the back.

dressing requires considerable time out of production. It should then be remembered that the C-frame press is essentially the convenient job shop machine for a variety of small-lot hand-fed work. The same frame construction which makes it so adaptable also makes it spring unavoidably on an arc. For that reason the life of fine cutting tools is consistently much higher in the straight-sided type of press.

It should also be noted in Fig. 354 that all working stations would be well within the natural area of the slide face and that a slide providing separate adjustment for each station could be furnished if necessary as in Figs. 347 and 348. Any unbalance in arrangement of stations from right to left would be likely to be of negligible importance, whatever the series might include, owing to the double-crank construction.

In point of convenience it is apparent that the working stations and particularly dies under the dial are accessible from the rear of the press in Figs. 354 and 356, but not in such presses as shown in Fig. 355. The roll feed unit for Fig. 354 could be mounted at the back of the press instead of the center of the dial, but might then interfere with the operating convenience.

Strip Feed Presses.—The automatic serving of combination blanking and drawing dies particularly by roll feeds has been mentioned. Such dies are also used in blanking, drawing and stamping from tin-plate, all sorts of tops and bottoms for tin cans and containers, a variety of screw

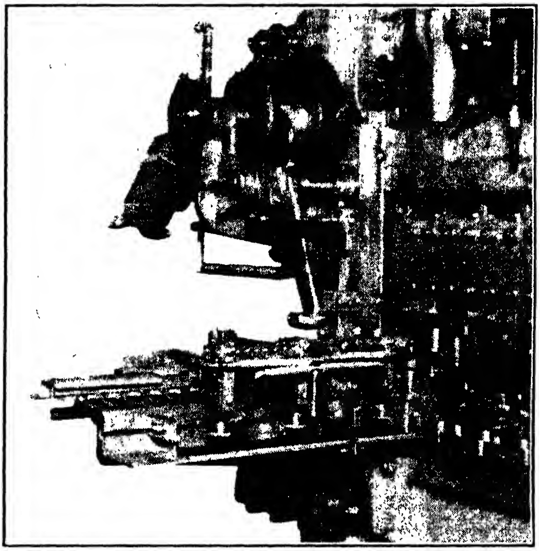


FIG. 357.—The automatic suction strip feed built on a seven-station multiple slide press.

caps and many toy, novelty and hardware parts. This list is limited to tin-plate either plain or lithographed, as such material has been commonly available only in short strip form which precludes roll feeding. A number of mills are now producing tin-plate in coil form, and a couple have gotten the cost down close to that of sheets so that better metal economy and improved production conditions promise much for it.

The short strips, however, are handled very rapidly in the newer automatic strip feed presses. As shown in Fig. 298, these are very massive C-frame machines fixed in an extreme inclined position. In some cases the usual C-frame characteristics are minimized by the use of substantial spacer tubes fitted between the top and bottom frame lugs, and

steel tie rods shrunk in place to a predetermined load. The strokes are necessarily fairly long to give a sufficient space and cycle for ejection of the product from the surface of the punch.

The strip feed mechanism may be used also on other types of equipment where short strips of tin-plate or other material are to be handled. Thus, in Fig. 357, it is built onto a seven-slide, bar-feed, multiple-operation press. Here strips of spring steel are sheared up into blanks in the first station to be carried across the press for a series of forming and piercing operations.

The automatic strip feed is so arranged that a stack of strips can be placed upon a supply table and renewed from time to time by the operator without interference with the constant operation of the machine. A blank is lifted from the top of the stack on the supply table by a set of suction fingers, and is moved back to a gauge on the feed table at a rate which is so proportioned relative to the speed and number of blanks per strip as to keep one strip following another in the die. An electrical trip gauge is furnished especially for working with lithographed stock to stop the machine in case two strips sticking together should get by the knurls furnished for their separation.

On the feed table is a set of reciprocating feed fingers to advance the strip step by step across the die by pushing on the end of it. A kickout finger on the far side of the die ejects the skeleton scrap after the last blank has been produced from each strip. When producing two or three blanks per stroke arranged in staggered relation on the strip for scrap economy, it is possible to increase the stroke of the feed bar and the spacing of the first and last fingers so the first and last feed strokes on each strip will be about 50 per cent longer than the average to avoid cutting half blanks. Individual feed fingers can be adjusted to compensate for inaccuracies in location of individual designs in a series on lithographed metal.

In some special cases strip feed presses are used to blank and draw a shell from the strip, then drop it back from the punch into a nest on a second die for an additional operation. As this is in the nature of a gravity feed it necessarily reduces the speed of operation. Automatic edge curling and stacking devices built on the back of strip feed presses are standard equipment for most can end work.

In rare cases strip feed presses have been adapted to the use of single row follow-dies. As the regular feed would push the end of the strip only up to the first station, an extension feed finger is required on the far side of the die to complete the feeding through the succeeding stations.

Electric Safety Devices.—The operating speeds of automatic press equipments have increased rather suddenly and now frequently reach a

point beyond the capacity of the eye of the operator to control. If the action of the feed and the tool is entirely positive this makes no difference. But there are instances in which a loose blank or piece of scrap may drag along or stick on the surface of the die, marking the product; or flimsy scrap may tend occasionally to buckle or tangle in the die; or some part ejected by air or gravity may not always get clear; etc. It is then necessary either to run at a low enough speed to permit the operator to see just what is going on in order to stop in case of emergency, or to maintain the speed and provide automatic means of detecting trouble and

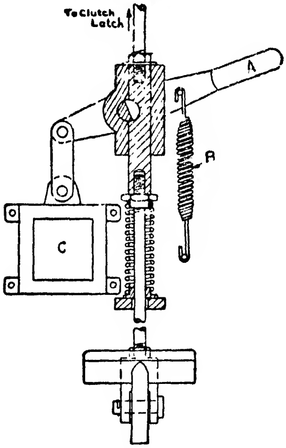


FIG. 358.—A standard solenoid connected to the treadle lock mechanism to control electrically the stopping of a "high-production press."

FIG. 359.—The treadle lock solenoid control on a high-speed roll feed press is here interconnected with a limit switch, to detect the end of a coil, and two remote-control push buttons.

stopping the equipment. The latter method permits the greater production and also eliminates danger due to inattention on the part of an operator.

It is the object here to discuss methods and devices for guarding expensive and delicate tools, especially at the higher operating speeds.

Most fast automatic presses have a positive mechanical clutch, controlled by a latch, which will stop the press as soon as the treadle lock is released. In an emergency the release of the treadle lock may be accomplished manually, mechanically or electrically. Of the two automatic means, electrical operation through a solenoid has seemed to be the most flexible.

Figs. 358, 359 and 362 illustrate the use of a solenoid arranged to control the treadle lock of a "high-production" press. In each case the constantly energized solenoid serves to hold the treadle lock in engagement and keep the press in operation. Breaking its circuit permits a spring to release the lock, freeing the latch, which stops the press. Experience seems to have shown that it is best to use a continuous rating solenoid and to keep the current on while the press is in operation. The alternative of energizing the solenoid only when the press is to be stopped is slower in action and is not so safe, in that electrical failure at some

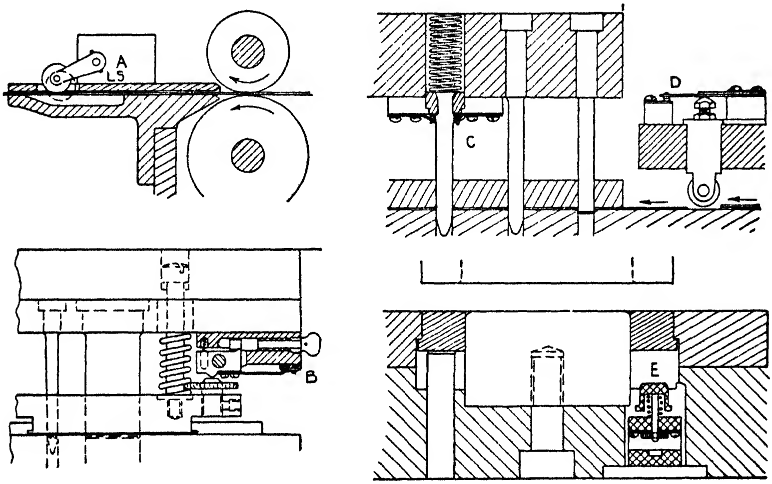


FIG. 360.—Emergency circuit opening devices for: (A) strip end or strip buckle, (B) checking metal thickness under a spring stripper, (C) pilot hole registry, (D) double strip detection, (E) double-action die protection.

point in the circuit puts the emergency stop feature out of commission without warning to the operator.

As shown in Fig. 358, the electrical stopping feature adds, to the standard treadle lock, only an extra long lever (A), a spring (B), a link and a small standard continuous-rating solenoid (C). The solenoid pull may just about balance the spring B, if the initial locking is to be done by hand. A more powerful solenoid will overcome the pressure of the spring (B) and operate the lock whenever the treadle is depressed.

Trouble Detectors.—There are a number of devices for breaking the solenoid circuit to stop the press, depending upon the type of emergency to be anticipated. Several of these are shown in Fig. 360.

To stop the press at the end of a coil of metal, or to stop when the strip meets some resistance in the die so that it cannot advance and

therefore buckles inside the feed rolls, a limit switch (*LS*) may be placed just after the feed-in rolls so that the switch roller is riding over an open space in the table as shown in Fig. 360 *A*. When the end of the strip passes, the roller must drop. If the strip jams and buckles it can only buckle downward, again permitting the roller to drop. In either case the circuit contact is broken in the limit switch and the press stops. Such a device is used inside the feed mechanism in Fig. 362.

To stop if the spring stripper of a follow-die or blanking die does not seat properly, a snap switch or contact breaker may be placed between the punch plate and stripper plate in the die as at *B* in Fig. 360. The spring stripper normally comes to just metal thickness distance from the

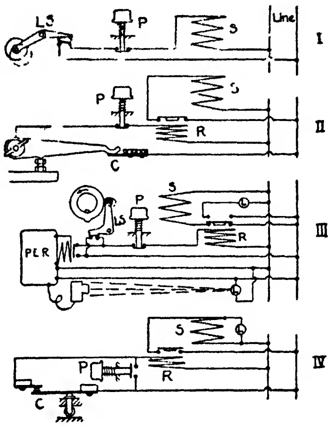


FIG. 361.—Typical detector control circuits.

C—contact or switch.
L—tell-tale lamp.
LS—limit switch.
PER—photoelectric relay.
R—relay.
S—solenoid, at treadle lock.

die surface. Therefore if two blanks are fed, or if a piece of scrap is pulled back by suction and pulled over on the die surface, where it is likely to mar the product, or if blanks are being carried in the scrap and one falls out, the double thickness of metal under the stripper plate reduces the distance between the stripper plate and the punch plate. The difference may be small if the metal is thin so that it may be advisable to arrange a multiplying leverage, as shown, to separate the contact points an appreciable distance. If the press motion is fast it is probably best to use some modification of the snap switch principle to open the circuit permanently to insure stopping. After clearing the die the device is reset as by pulling out the knob in Fig. 360 *B* or readjusting the thumbscrew in circuit II, Fig. 361. If the press motion is slow it may be suffi-

cient to use simple spring contacts such as those shown in Fig. 360 *D*. If the metal thickness is considerable, so that no multiplication of motion is required, a standard push-button element or unit assembly (*see* Fig. 360 *E*) may be mounted in the punch plate with an adjustable set screw on the stripper to contact with it. Such a unit has the advantage of providing all necessary contacts, springs, insulation and binding posts at a small cost.

To stop in case of a misfeed in a follow-die, a spring-backed feeler

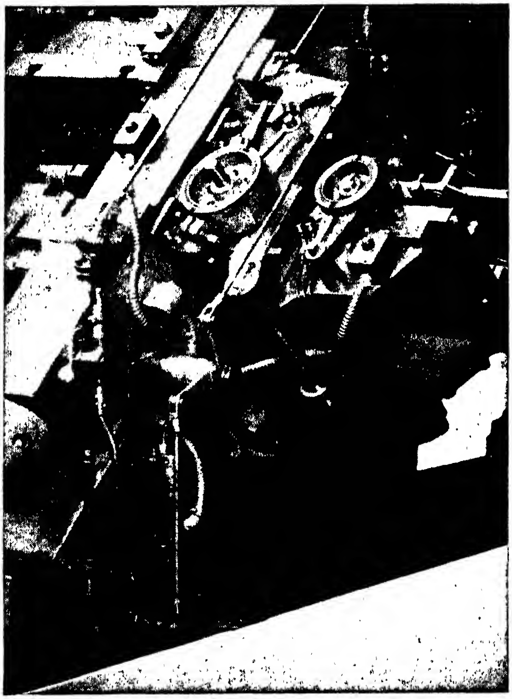


Fig. 362.—Solenoid control on a "high-production press" with four remote-control push buttons and a buckle detection limit switch to safeguard a $6000 compound die.

pilot may be used as in Fig. 360 *C*. This pilot must be somewhat smaller and freer than other pilots in the die so that it enters the pilot hole without being affected by the normal work of locating the strip. In case of a serious misfeed, such that other pilots break through the strip, this one strikes the solid metal and backs up, breaking the solenoid circuit and stopping the press.

To stop in case of feeding double blanks a feeler roller may be used as in Fig. 360 *D*. This is similar in principle to a limit switch but must

be quite sensitive. It is used particularly on high-speed automatic strip feed presses, where sheets of lithographed or oily tin-plate are likely to stick together at times. The extra thickness to be detected is, of course, about 0.009 to 0.012 in. As the motion of the sheet feeding mechanism is relatively slow, there is time to stop the press by closing the circuits and energizing the trip solenoid instead of by de-energizing as is the normal practice. This device may be used also in connection with magazine and push feeds.

To stop in case of a misfeed at a drawing operation, as in a multiple slide press, a push-button element or other contact breaker may be mounted under the blank-holder ring as in Fig. 360 *E*. If a shell is not properly located and is jammed or buckled up between the blank-holding surfaces, the double or triple metal thickness causes the blank-holder ring to travel farther than usual and break the control circuit.

To stop the press, if a stamping, which is being discharged from the die by air or gravity, does not clear at the proper point in the cycle, it has proved possible to use an electric eye or photoelectric relay, in conjunction with a timing limit switch controlled by a cam on the press shaft. Such an arrangement is suggested in circuit III of Fig. 361. Either the stamping should pass a given point at a given time, or it should be clear of the danger zone at a given time. Then it would (or would not) intercept the rays of a light source directed at the light-sensitive receiver, with a corresponding effect through an amplifying tube upon a sensitive relay and control contactor. As the presence or absence of the stamping must be recorded in relation to a specific instant or period in the press cycle, a cam-controlled limit switch may be arranged in parallel with the photoelectric relay, to open the circuit at the instant the latter should close it.

Circuits.—Fig. 361 is arranged to show methods of connecting standard electric units for the services just described. The solenoid for releasing the treadle lock and stopping the press is indicated by the letter *S*. In each circuit a push button, *P*, is shown which may be used for stopping a press at the will of the operator. In Fig. 362 are shown two out of four such push buttons, which were placed at various convenient spots about the press.

Circuit I in Fig. 361 is the simplest, being so wired that the full current drawn by the solenoids, *S*, passes through a normally closed push button, *P*, and normally closed limit switch, *LS* (Fig. 360 *A*). This will cause some arcing to the detriment of the contact surfaces when the circuit is opened at either point. Therefore to protect these contacts it is usually better practice to put the push buttons and trouble-detecting devices on a control circuit which will draw comparatively little current.

In that control circuit is placed a standard relay or contactor to open or close the solenoid circuit.

Thus in diagram II, Fig. 361, the solenoid, *S*, is on a circuit by itself which is kept normally closed by the relay, *R*, in the control circuit. With it are included a push button and a contact point, *C*, of the multiplying leverage, thumbscrew reset type for similar service to Fig. 360 *B*, detecting double metal thickness under a spring stripper plate. All these devices are in effect normally closed switches, as the press is to be stopped, in emergency, by opening the circuit. In general any of the detector devices in Figs. 360 and 361 may be substituted for any of the others to suit the needs of the case, provided that the normally open or normally closed feature is followed consistently. A number of push buttons and detector devices may be used on the same circuit when required. If so they should be in series for the quick-acting normally closed type, diagram II; or in parallel for the slower, but more economical, normally open type, diagram IV.

Diagram III in Fig. 361 is arranged to show the synchronization of a detector with some particular period in the cycle of an automatic press. The control circuit includes the normally closed relay, *R*, which governs the separate solenoid circuit; a normally closed push button, *P*, for manual control or jam detection; a limit switch, *LS*, the roller of which rides on a cam on the press shaft to keep the circuit closed except at the time the detector is to function; and the detector. In this case a photoelectric relay or electric eye, *PER*, is shown as the detector. It is arranged on its own circuit with a lamp to serve as light source, receiving and amplifying tubes, sensitive relay and a contactor which serves as the link to the control circuit. This contactor and the mechanically timed limit switch must be arranged in parallel to get complementary opening and closing action while retaining a normally closed circuit. A red warning lamp, *L*, may be connected through the normally open poles of the relay so that it will attract the attention of an operator when the press stops. This may be of value when several strip feed presses, or simple coil stock jobs, are being run automatically under the control of one operator.

Diagram IV, Fig. 361, is an example of the normally open type of circuit requiring parallel rather than series hook-up. The circuit may be closed either by the two-blank-detector roll, *C*, or by the push button, *P*. Either will energize the relay to close the solenoid circuit for stopping the press. A red tell-tale lamp, *L*, may be placed in parallel with the solenoid to indicate stopping. As current is drawn only when the press is to be stopped this arrangement is a bit more economical than the normally closed type. On the other hand there are several handicaps

because of which a normally closed type is usually favored. In case of electrical failure at any point the latter type stops the press at once, while the normally open circuit gives no warning of the trouble until an emergency arises, when it is too late. Note too that a normally open push button requires sufficient pressure to contact positively at both points; but in an emergency it is quite likely to receive only a light and hasty touch which does not actually close the circuit. It seems too, that snappier action results from breaking circuits, and de-energizing magnetic devices, than from the reverse process.

Costs.—Design, mechanical accessories, and wiring all enter into the cost of electrical controls, but a rough idea of the expense involved may be obtained from following list prices of standard electrical control units. These are much less costly, in general, than home-made devices for the same purposes.

A-c. relays or magnetic switches	\$10.00 – \$20.00
Limit switches	\$5.00 – \$18.00
A-c. solenoids, continuously rated	\$12.00 – \$60.00
Photoelectric relay units	\$87.00
Push-button elements	\$1.25 – \$1.75

CHAPTER XV

DIVERSIFIED PRODUCTION

It seems strange that diversified production should follow automatic production in this discussion, but that is the sequence, in that the one was fostered by quantity requirements achieved in automobile manufacture, and the other was a necessity to meet rapidly changing airplane development. Earl Cannon has put it concisely, that out of the

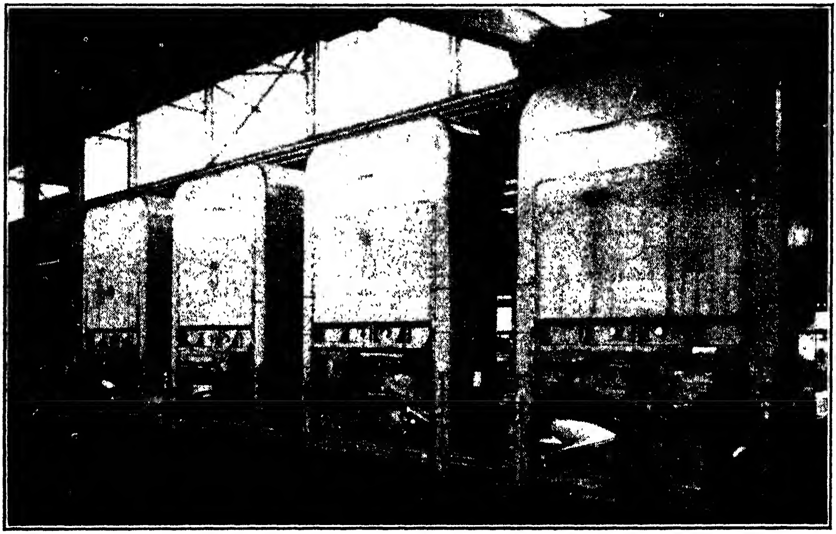


FIG. 363.—The "front fender line" which completes a series of trimming, flanging and punching operations as right- and left-hand drawn fenders, for a well-known car, are passed along the front and rear of the presses.

period of high-production machinery and rigidly standardized assembly lines, has evolved the flexible assembly line for a diversified or changing product. It is backed by, and in part made possible by machinery with exceptional flexibility of control and adjustment and by adaptation of tools and tool materials favoring rapid and easy construction and change. Accompanying all this, and very definitely influencing it, has been the expansion of the horizon of engineering materials.

A mass production high point in rigid assignment of well-tooled machines, in sequence location for standardized parts, was the model

"T" Ford. At that time, however, a model change required that production cease completely for a considerable period. Subsequently diversification of accessory equipment, body styles, colors, and interior trim necessitated greater flexibility in control of feeders to the assembly line. Back of feeder and sub-assembly lines the trend remained to shift fine dies and line set-ups, Fig. 363, as infrequently as possible and likely only for model changes. In general, quantities were large, and the effort was made to keep parts flowing from step to step at a steady, fast pace and without intermediate storage. Such methods naturally make for maximum economy, but in warplanes, changes were too frequent and assembly too complex and slow to permit storage of the output of quantity production runs.

Metal plane manufacture, like early automobile building, began with relatively simple equipment. Some of it was borrowed from the practice of duct and furnace makers. Squaring shears, rotary shears and small punches took care of most of the cutting operations. Bar folders, power brakes (Fig. 364), and bending rolls handled a variety of bending operations. Brakes have also found considerable application in the production of office files and furniture, trucks, cars, and other products of straight-line design requiring a variety of bends, Fig. 365. Bottoming loads, which tend to frequent overloading, and the central working stresses, which permit simple sections, have favored rolled plate construction. Forming operations allied to shallow drawing were performed in large area drop hammers, often using reducing piles of leather shim rings to simulate blankholding. This left much to the skill of the operator and to subsequent finishing of wrinkles and outline with a hand hammer.

Warplane output demanded production with flexibility, fluid designs and steady flow without accumulation of too many parts ahead. At about the same time complete streamlining did away with most of the straight lines and required more tooling. To meet the flexibility of changing design such tooling had to be cheap. To produce economically a few dozen parts of a kind per run, usual tool set-up times had to be practically eliminated. Ground plate blanking dies and rubber die forming are typical of the diversified production solutions. In both, cheap dies are located by eye with little or no press adjustment, and usually without even clamping in position.

Ground plate *blanking* dies developed apparently around Minneapolis for small-lot requirements prior to the warplane problem. Their economy was achieved by the combination of jig boring, nibbling, band sawing and band filing of thin steel plate in a production die-making method. The plate, rolled and ground to an eighth or three-sixteenth

thickness may be a carbon steel or alloy steel, machinable but hard enough without subsequent heat treatment to cut a number of low-

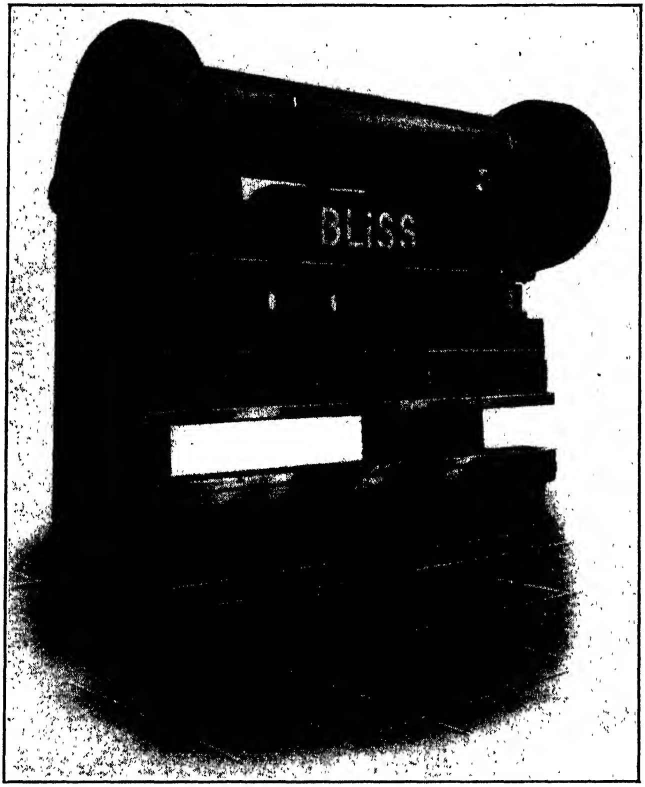


FIG. 364.—A power brake for a variety of straight-line bending operations, in this case up to ½ in. thick by 144 in. long in steel.

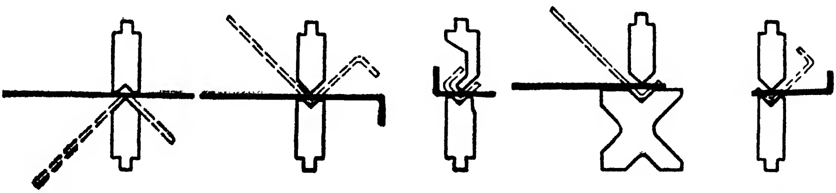


FIG. 365.—Typical brake bending operations to which certain curving, corrugating, seam forming and other operations (Chapter V) may be added.

carbon steel blanks or a substantial quantity of soft metal blanks. The die and the stripper which serves also to guide and align the punch are cut and finished together to the blank profile and mounted on a

block with space between them for the strip to be blanked. The mounting block and block back of the punch are of uniform height so that the inclinable (or straight sided) press may be kept set at the same die height. After each blank is punched the operator slides the die out, knocks out the blank and punch, moves the strip into position for the next cut, relocates the punch in the fixed stripper and pushes the assembly back under the press ram for the next stroke. Direct labor is relatively quite high, but for short runs the saving of set-up time appears to warrant it.

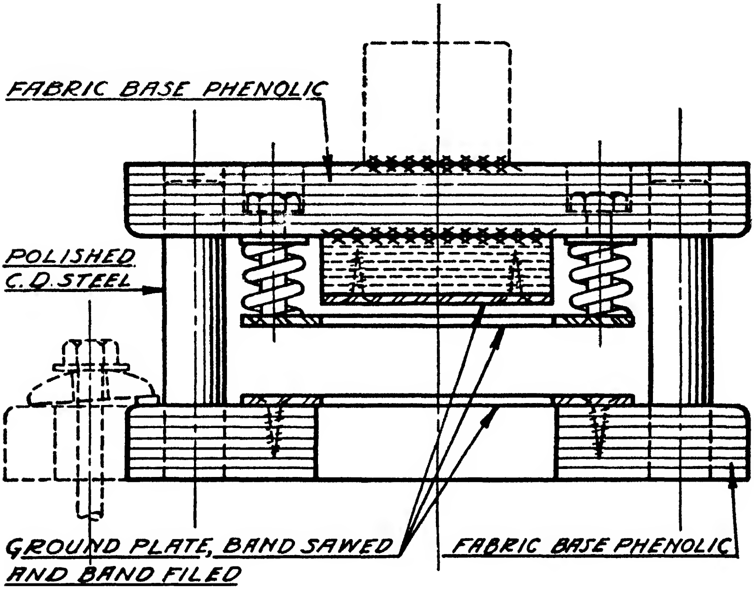


FIG. 366.—Easily worked die materials for limited lot blanking of the softer metals. See also Fig. 402.

In view of increasing use of synthetic materials, Fig. 366 suggests a more conventional arrangement of ground plate blanking dies for easy construction. Such dense, high impact fabric and phenolic plastics as Synthane and Micarta, which machine at woodworking speeds, have requisite bearing qualities and stability for limited quantity die-set usage.

Materials, new and old, changing mixtures of materials and proper physical test data to aid in working and using materials continue to be a major problem. Warplane production expanded the output of aluminum alloys, magnesium, transparent organic plastics, paper and cloth filled with thermosetting plastics, etc. The non-metallic materials and their plastic states are discussed in following chapters.

Magnesium, pure or alloyed for increased hardness, as with manganese, is recommended by its extreme lightness. Like zinc, it has limited plasticity at atmospheric temperature, but if heated above its recrystallization range, to 600–650° F., deep drawing is possible. Piercing, blanking, bending and forging operations follow normal lines. Surface protection from oxidization and cleaning up of finely divided scrap are necessary fire precautions.

Heat-treatable or dispersion-hardening aluminum alloys were found to have an undue tendency to tear if hurried in drawing operations.

FIG. 367.—An Alclad pan drawn and stamped at Vega Aircraft in a quickly adjusted Hydrodynamic double-action press, using the bottom cylinder for blank holding, the outer slide for drawing and the inner slide for forming the steps. (*Courtesy The Modern Industrial Press.*)

The interference with slip-plane action of copper particles in the aluminum space lattice seemed responsible, and it was found that while commercially pure aluminums would draw at crankpin velocities of 100 ft. per minute, the high-strength alloys had to be slowed to around 35 ft. per minute. Stainless steels seemed to take difficult draws best at even lower speeds.

Strong aluminum alloys clad with a thin protective layer of pure aluminum were found to scratch and mar too easily on cast iron and steel dies. To solve this zinc and zinc-aluminum alloy dies proved

satisfactory and were also found easy to remelt and repour in plaster of Paris molds when models changed. Wood and Masonite punches and stretching forms worked out for some applications because of the light loads involved. Later, resilient cast phenolic[1] and other synthetic resin punches were successfully used, being poured directly against the contour of mating zinc-alloy dies.

Such dies for deep forming and *drawing operations* were used first in rope lift and pneumatic hammers adapted from metal ceiling work. Later the deep draws went into double action toggle drawing presses with motorized long adjustment and inching control for motor drives arranged for suitably reduced speeds. For flexible diversified production purposes, self-contained hydraulic double action presses, Figs. 291 and 367, with very versatile electric control systems proved fast and

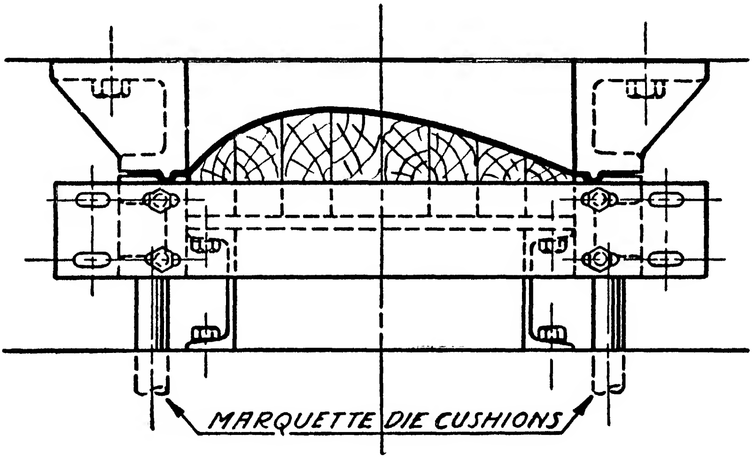


FIG. 368.—Double-action stretching of simple curvature skin sections over wood or plastic punches with adjustable gripper sections.

accurate to set up, turning out excellent stampings with a minimum of spoilage. Aside from soft die materials used, die design principles were essentially the same as was outlined in Chapter VIII. Draw die corner radius tended to increase over six times the metal thickness for Alclad aluminum and to decrease to around $2\frac{1}{2}t$ for stainless steel and to similar low values for drawing some of the synthetic thermoplastics.

Stretching of simple contours in which sheet material must take a set to suit some outline is a modification of double-action drawing practice as described in connection with Figs. 142, 169 and 170. It requires

[1] "Plastic Punches," Leon Champer, Plastalloy Co., The Modern Industrial Press, February, 1943.

that the material be firmly gripped at the edges in order to set up strains exceeding the yield point of the metal. For airplane skin surfaces some sections are simple enough to be formed in three-roll bending rolls. Others involving change of radius or more complex curvature required stretching but were simple enough to permit gripping along

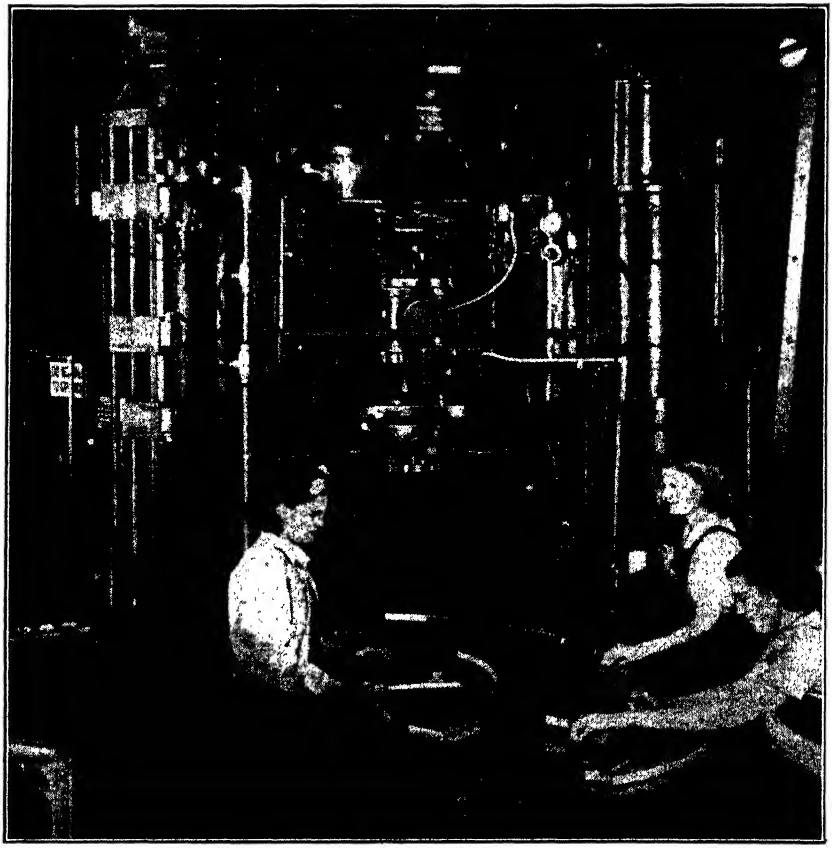


FIG. 369.—A crew of three at one of the slides of a six-slide press arranges punches and blanks for rubber die forming to suit whatever order or quantity of stampings may be required. (*Courtesy Douglas Aircraft Co.*)

only two edges, Fig. 368. For aluminum the punches were made of zinc alloy, wood and various more durable synthetic wood compositions. As long as there are no reverse shapes or curves, male punches only are required. Gripping members may be adjustable or movable and the combination may be set up in any double-action press or double crank with suitable die cushions.

Perhaps the outstanding press contribution to diversified production was a type which came as a climax to the development of *the rubber die process*. The early use of rubber in dies for bulging, stripping, forming, etc., was revived and expanded especially under Henry E. Guerin, The Douglas Aircraft Company,[2] Santa Monica, California. By confining a plyable rubber pad and supplying sufficient hydraulic pressure back of it, the rubber could be forced without adjustment to become a mating die for any punch or group of punches which might be placed on the die slide or base plate. As shown in Fig. 369, a number of soft steel, zinc

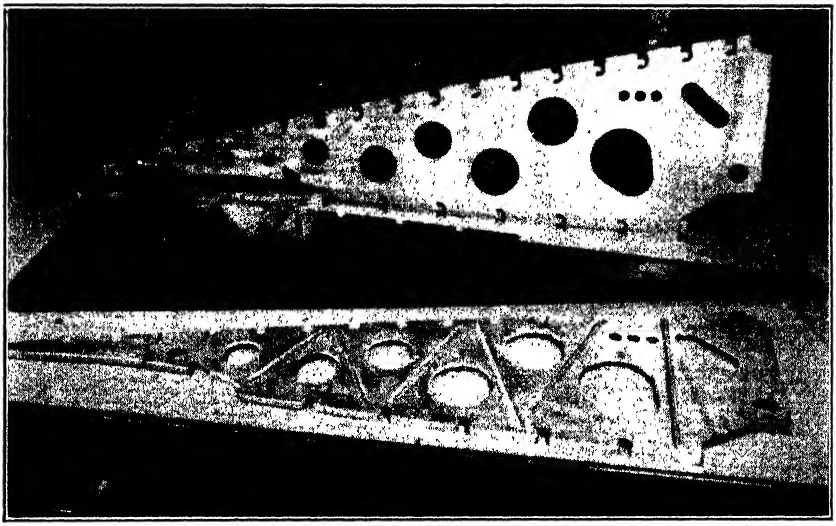


FIG. 370.—An alloy-aluminum wing rib and blank with Masonite punch for use in rubber die forming. (*Courtesy Douglas Aircraft Co.*)

or plastic board male punch plates may be placed in any convenient positions on the die slide and aluminum blanks layed on top of them. The loaded die slide is moved automatically into the proper position under the press ram, and the rubber mattress in a confining ring of iron or steel is driven down over the whole area. This forces each sheet-metal blank to conform closely to the exposed profile of its punch for the confined rubber is substantially incompressible. Average pressures up to about 1500 or 2000 psi seem adequate for the bulk of the forming (principally bending) operations performed on alloy aluminum up to $\frac{1}{16}$ in. thick in this way. Various tricks are used as required to localize more pressure as by adding a bit of plastic or harder rubber at critical points.

[2] U. S. Patents 2,055,077, 2,133,445, 2,190,659.

Fig. 370 shows at the bottom a typical formed part of alloy aluminum, in the center a forming member or punch as used in the rubber die presses and, at the top, the blank required. In many cases such blanks are routed out for the limited quantities required:—A template is prepared by screwing down to a straw-board plate a set of different blanks arranged closely to get maximum economy out of the metal-sheet size. On another synthetic wood plate a stack of aluminum sheets are screwed or clamped firmly to be cut up. A pantograph routing machine follows the template and cuts the stack into blanks using a little two-blade milling cutter motorized for several thousand rpm. The forming punch in this illustration is made in two parts of Masonite, a dense and durable synthetic wood. The lower portion is lifted to get the forming up into the rubber better. The upper portion is cut out to the contour of the part in wood-working tools and possibly coated with a soluplastic resin to improve surface hardness, oil resistance and wear resistance. The forming edge has about a 1/16 in. radius and is undercut at about an 8° angle for such work, to permit overbending for approximate spring-back compensation. The notches in the blank assist in rubber bending and especially in avoidance of wrinkling in bending around an outside arc contour as there is no blank-holding action. The plastic sheet stock is also used as a backing for thin sheet (1/16–1/8 in.) carbon-saw steel or chrome-vanadium steel, unhardened, for temporary blanking dies for soft metals.

Highlighting both diversified production equipment and the rubber die method are the great presses in Figs. 371 and 369. Obviously inexpensive die members just described, which do not require mating members, may be "set-up" with extreme ease be it for ten or a hundred pieces. A crew of 18 to 24 serve the six-die slides, arranging the forming punches, placing blanks in position on them and locating auxiliary bits of steel and rubber to aid in the forming. As each die slide is loaded an operator pushes a button and a completely automatic electric traffic system takes over. The heavy slides are moved in to the working position without shock and in whatever order they are made ready. The oblong rubber mattress weighing about a ton and confined in a substantial holder, swings automatically into alignment with the particular slide load to be formed. The ram descends and applies a pressure which has been adjusted to suit the particular grouping of jobs being run on the particular die slide. After the initial setting of the six pressure switches, this pressure selection is automatic, whatever the order in which loading of slides may be completed. Warning lights tell which slide will be the next in, if more than one are ready at once. Transparent plastic windows guard the working space. Earlier units used

one, two, three and four loading positions, but it was found that the six-slide equipment made the most economical use of the press investment. The equipment is, of course, a self-contained unit with pumps, motors, controls, reservoir, cooling and filtering equipment, etc., arranged for highly efficient and smooth cycle operation.

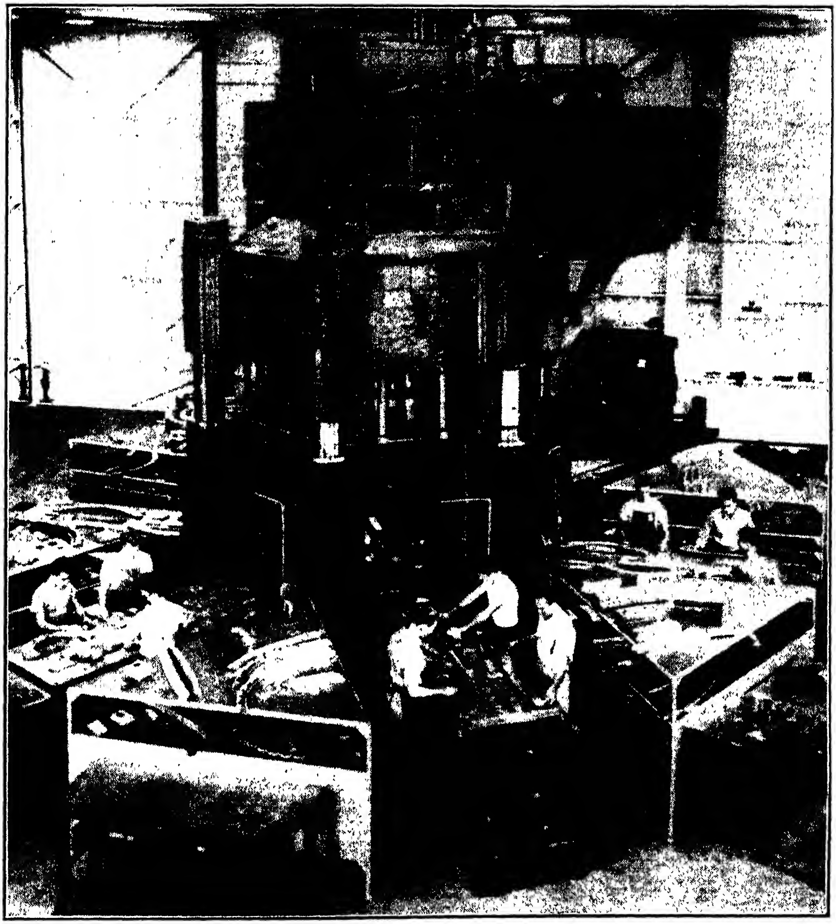


FIG. 371.—A 2500-ton capacity Bliss Hydrodynamic Six-Die Slide Press for rubber die diversified forming operations. (*Courtesy Douglas Aircraft Co.*)

It is obvious that the most economical results in diversified production will result from the use of equipment which is best suited to fast-changing and convenient, quick adjustment to suit a variety of limited quantity work. Hydraulic pressure adjustment for bottoming operations, hydraulic or pneumatic adjustment for blankholding pres-

sures in drawing and quick electrical adjustments of die space, speed change and possibly of stroke seem to be the ranking machine features for economy in small lots. Such equipment promises much for production of light-weight trains, special model automobiles, custom-built housing, home accessories, etc.

CHAPTER XVI

PLASTIC STATES, METALLIC AND NON-METALLIC

WHEREAS the science of the "Plastics" is developing under the revealing though sometimes diffused light of organic and inorganic chemistry; the art dates back to the gum on the Indian's birch bark canoe, and farther back to mud huts. Metallic, organic and ceramic materials, and combinations of them, employ the mass-production method of dies or molds, with presses in one form or another to impel plastic flow.

Commercially, *plasticity* refers to the ability of certain useful materials to be pulled or pushed into useful shapes. Many metals, iron, copper, aluminum, nickel, silver and many of their alloys are plastic in their frozen or crystalline state. These and other metals, glass, silicones, natural and synthetic resins, etc., are plastic (forgeable, formable) in their heated or semi-fluid state. Other materials are plastic or shapeable when moistened with a suitable solvent as putty, plasticene and paper (moistened with water). The materials having characteristics of plasticity in these three plastic states are described, in order, as *crystoplastic*, *thermoplastic* and *soluplastic.*

Thermosetting and *solusetting* materials should also be distinguished here as they interlock closely in many respects with plastic materials, but for practical purposes they lack plasticity. In general these are mixtures of fillers, flow aids and setting adhesives, powdered for mobility. In the presence of heat or a solvent they undergo a chemical reaction or change which solidifies or sets the binding adhesive. By reason of the chemical change they cannot be made plastic for further change of shape. Typical of thermosetting materials are the common phenolic resins (carbolic acid and formaldehyde) as the binder; mixed with a lubricating plasticizer and such fillers as wood-flour or asbestos for compression molding in heated dies; or impregnated into paper, cloth or plywood with alcohol or other solvents and then baked flat or to shape under similar heat and pressure. The sulphur reaction in rubber molding and the copper-tin reaction in the sintering (baking) of the molded powdered bronzes also qualify such processes as thermosetting. Portland cement as the binder with sand as filler and water as the solvent may typify the solusetting process. "Cold molded" electrical parts, plaster blocks, paints, etc., are widely different examples of solusetting.

We should also distinguish the term "*cold-set*" *materials* as this description is sometimes applied to thermoplastic materials, because after addition of heat to make them plastic they must cool to resolidify.

Perhaps cohesion and adhesion are useful to help distinguish the plastics and the setting mixtures. In thermosetting and solusetting methods the added bonding agent or adhesive creates a surface attachment by means of chemical combination. Among the plastics, on the other hand, mutual cohesion of molecules (mon-atomic or complex) permits rearrangement and reestablishment of electro-magnetic bonds in the plastic range.

Solubility.—Common salt, which might be described as soluplastic, will go into solution in water up to a certain percentage. Its molecules tend to disperse comfortably among the water molecules until they become crowded, when they crystallize out of a supersaturated solution, or until the water evaporates and they again cohere amongst themselves quite tenaciously. Gold and silver dissolve in each other (molten) in any percentage, but it is of interest that the intermediate alloys (when cold) are less plastic than either of the pure metals (Fig. 12, page 15). Iron carbide dissolves in iron up to 0.83 per cent. Substantially pure iron (deep drawing steel) is found to be plastic in cold working operations up to about 65 per cent reduction. Iron carbide dissolved in iron (dispersed through it as pearlite) strengthens the "steel" by interference with slip-plane movement (Fig. 117, page 122, and Fig. 122, page 127) in the cold or crystoplastic range. Another interesting quirk of solubility is illustrated by Fig. 13, page 15. Up to 36 per cent of zinc dissolved in copper (alpha brass) has considerable cold plasticity. About 40 to 50 per cent of zinc dissolves in copper to make beta brass which is suitable only to hot forging (thermoplastic). Further increasing the zinc percentage results in a chemical compound Cu_2Zn_3 which is too brittle for plastic working, either hot or cold.

Temperature and Plasticity.—Many elements, compounds of elements and mixtures (all of which must be distinguished) change as their temperature rises through more or less familiar states from solid, through "plastic," to liquid, to vapor and gas. Water, varying from solid ice to liquid (water) to steam, is familiar, but its moldability in the slushy stage is debatable, unless we consider snowballs and ice cream. Among the common "thermoplastic" hydrocarbons, the lowly paraffin candle will mold itself into some sad and droopy shapes on a hot day. However, on a cold day the candle is not plastic and will break. Typical of some synthetic molding mixtures, asbestos fibers or finely divided wood with pulverized thermosetting resins for binders and talc or oily lubricants as plasticizers, are mobile rather than plastic up to the time that

setting heat is applied. The mixed mass is hot plastic only during the extremely brief setting period. The speed of this reaction has delayed and complicated the application of thermosetting materials to injection molding.

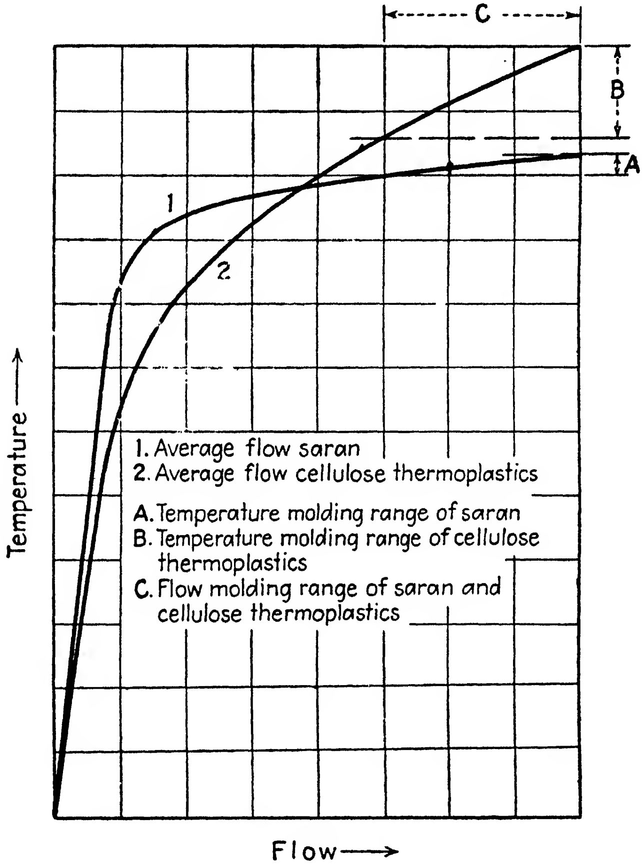


FIG. 372.—Plastic flow versus temperature, showing that some thermoplastic materials may be worked through a wider and less sensitive temperature range than others, though possibly at a sacrifice of some other properties. (*Courtesy The Dow Chemical Company.*)

Two periods of plasticity are noteworthy in some materials. Thus, commercially pure iron (deep drawing steel), aluminum, copper, nickel, lead and some of their alloys are of a sufficiently simple crystal pattern or arrangement so that they may be cold worked in the crystalline state below their annealing or recrystallization temperatures; and may be hot worked in the amorphous state of increasing atomic distances and

shifting inter-atomic bonds between the crystalline and fluid states. The limiting temperatures of this thermoplastic range may be relatively wide, as for beta brass, or relatively narrow, as for copper. And lead is normally worked in its hot range as it anneals at normal room tem-

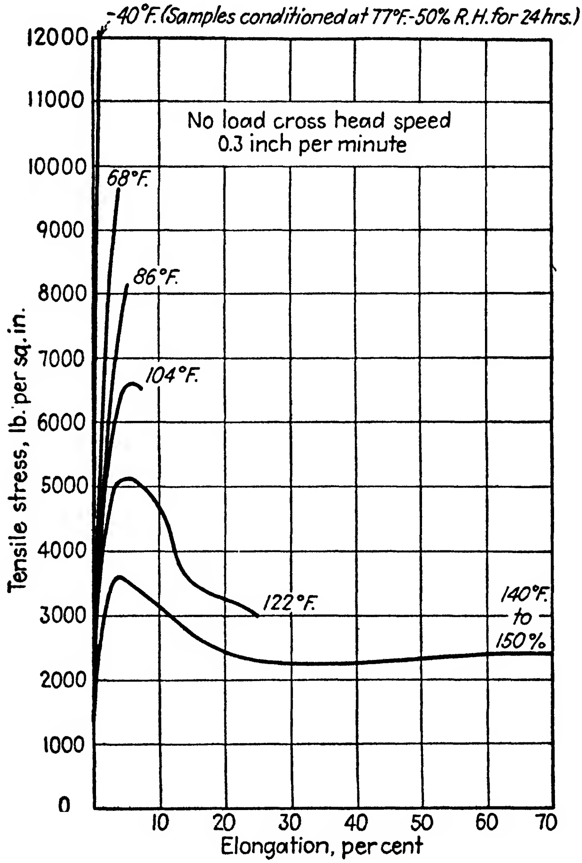


FIG. 373.—While breaking without distortion and with increasing elastic limit below 100° F., Lucite shows considerable plastic range with some remaining elastic recovery when warmed up to 140° F. DuPont recommends 248° to 280° F. for simple forming, 300° for multi-curve forming, 305° to 350° F. for compression molding and 370° to 475° for injection molding. (*Courtesy Plastics Dept., E. I. DuPont DeNemours & Co.*)

peratures. Note also that zinc, tin and magnesium are thermoplastic only, for practical purposes, as their crystal structures are too complex for appreciable slip-plane movement. However, tin anneals below room temperature and zinc and magnesium require comparatively

little added heat to give their atoms sufficient mobility for plastic change of shape.

Among the synthetic resins, cellulose acetates and methyl methacrylates are both thermoplastic, and the latter appear to have an appre-

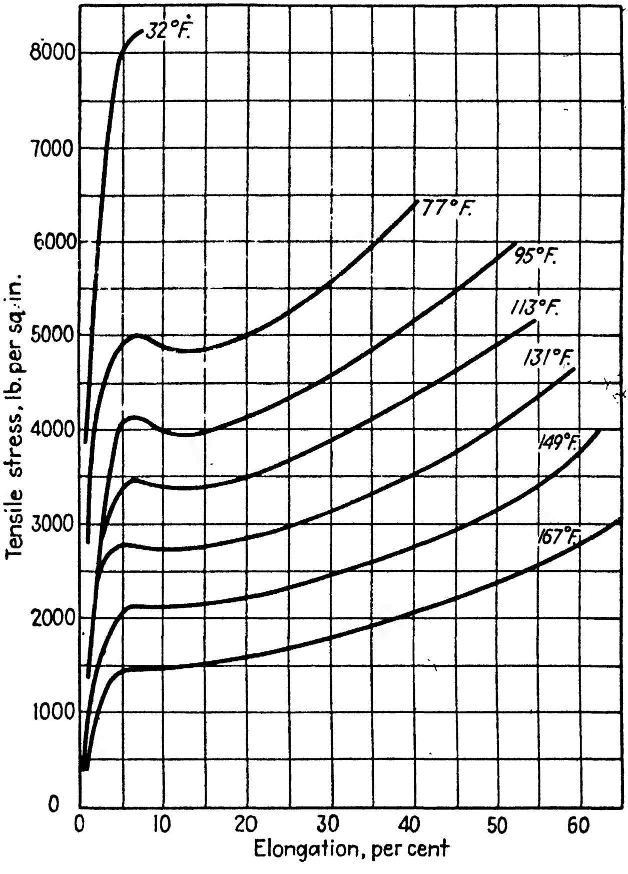


FIG. 374.—Approaching crystalline brittleness with high elastic limit at 32° F. Lumarith (cellulose acetate) indicates increasing plastic range and decreasing elastic recovery as temperature rises. For such material, working temperatures recommended are: forming, 275° to 280° F.; compression molding, 260° to 390° F.; and injection molding 340° to 450° F. (*Courtesy Celanese Celluloid Corp.*)

ciably wider hot-working range which gives the operators more handling time. Fig. 239 for metals and Fig. 372 for two types of thermoplastics show relative temperature plasticity relationships. See also Table XXI, page 262, for different steels. Below the hot plastic range the methyl methacrylates become brittle, Fig. 373, but the cellulose acetates,

Fig. 374, show a combination of elasticity and limited plasticity down below room temperatures. At room temperature, the elastic spring-back of the latter is so high as to offset most cold forming. Thus, within the elastic limit of the surface material, Lumarith (a cellulose acetate) may be bent to a radius of about 70 times the sheet thickness, whereas a deep drawing steel would be limited to a radius of about 1100 times its thickness or one-fifteenth the spring-back.

Elasticity and Plasticity.—In both the cold plastic and the thermoplastic range, elasticity and plasticity have considerable inter-relation with consequent interesting effect upon plastic working operations. In Figs. 15, 123 and 185 it was shown that the elastic limits of bronze, copper and steel are increased as the metals are cold-worked and strain-hardened. At the same time, the remaining plastic range of these materials becomes progressively less until annealing and recrystallization becomes necessary. The elastic movement is represented, of course, by the nearly vertical increase of load without appreciable yielding of the material. The subsequent substantial compression or stretch of the material with moderate change of applied force represents plastic movement. Fig. 14 is also of interest, showing the increasing elastic limit and decreasing crystoplastic range of plastic iron as non-plastic iron carbide increases. Now to return to the thermoplastic range, Figs. 373 and 374 show similar stress-strain curves for synthetic resins at different temperatures. The sudden termination in the elastic curves at the lower temperatures shows clearly their lack of plasticity in the crystalline state and the differences in their freezing points. Fig. 374 shows the lowering elasticity and increasing amount of plasticity as the temperature increases, although it is not carried down to the producers recommended forming temperatures or to the semi-fluid injection molding or die-casting temperature. The dip in the cooler curves (like that in Fig. 186) indicates a change of directional strain in the crystal structure. The subsequent rise shows work hardening, and would be eliminated by slower movement or sufficient time for stress relief.

The Lumarith curves also indicated why the higher temperatures (275° to 280° F.) are recommended for forming. Obviously work hardening and resistance will be less and capacity for flow or rearrangement will be greater. Also, with a lower elastic range a lesser holding or stress relieving period will be required while molecules ease themselves into a set in the new positions. To be sure, similar spring-back tendencies are found among the metals, but due to lower elasticity thereof they are neglected, or allowed for, or corrected. Thus in V-die bending operations a squeeze at bottom stroke sets up a compressive stress to counteract a remaining tensile strain in the surface fibers.

Modulus of elasticity, being somewhat misnamed, is sometimes misleading. It is rather a modulus or measure of rigidity. The modulus of elasticity for the metals is up in the millions; for synthetic plastics, many times more elastic than steel, it is down in the hundred thousands; and for the rubbers, stress-strain curves indicate it is way down in the hundreds. Even when the modulus is constant as for the steels, the maximum stretch or elastic deflection (elastic limit ÷ modulus of elasticity) may vary widely as between an annealed iron and a dispersion hardened tool steel, Fig. 14. Here again deflections are materially greater, though widely variant, among the synthetic plastics, and greatest among the related elastomers.

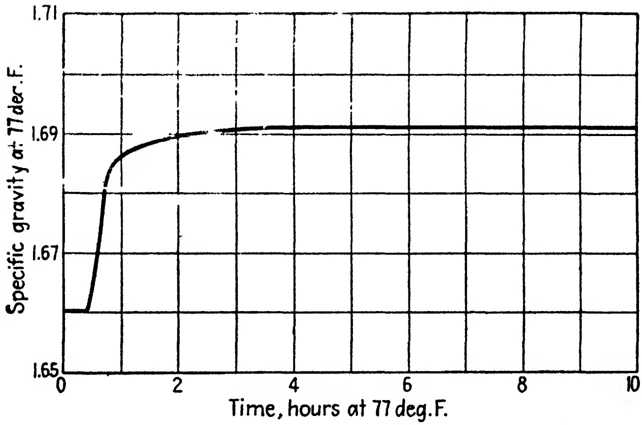


FIG. 375.—Increasing specific gravity of vinylidene chloride during recrystallization from the mixed arrangement of the worked thermoplastic state (1.66) to the close and orderly packing of the crystalline state, improving further with time for crystal grain growth. See also Fig. 180. (*Courtesy W. C. Goggin, R. D. Lowry, The Dow Chemical Company.*)

Structure and Plasticity.—Pure metals and solid solution alloys, such as alpha brass, are monatomic, one atom per molecule. Compounds combine several atoms per molecule. Thus, iron carbide Fe_3C combines 3 iron atoms and one carbon atom into a molecule. Cellulose triacetate $C_6H_7O_2(COOCH_3)_3$ combines 12 carbon atoms, 16 hydrogen atoms and 8 oxygen atoms into a complex molecule having a molecular weight nearly six times that of iron yet so large and spaced so far apart that a given volume weighs less than one-sixth of the same volume of iron. Freezing into crystalline form, the intermolecular forces tend to establish an orderly and balanced arrangement, Fig. 117, page 122. In discussing the metals, it was pointed out that this orderly arrangement may be disturbed and unbalanced to the extent permitted by the

(crysto) plastic range of the material. Internal stresses may then be relieved and orderly crystal structure restored, Fig. 127, page 135, and Fig. 180, page 199, by annealing or adding heat so that electronic energy or activity increases to such a point as to rotate the molecule again into proper relation with those around it. The orderly internal structure of an annealed metal makes it denser than in a disturbed, cold-worked

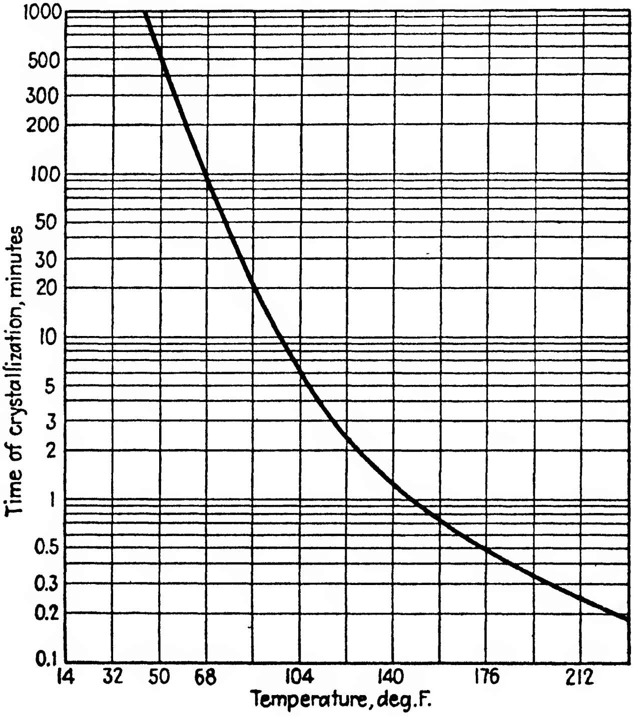


Fig. 376.—Time required at different temperatures to cause recrystallization or inter-molecular stress readjustment of vinylidene chloride (Saran). This recrystallization range is typical also of the metals. (*Courtesy W. C. Goggin, R. D. Lowry, The Dow Chemical Company.*)

metal. Similarly Fig. 375 shows that recrystallization of a worked thermoplastic resin (vinylidene chloride) also increases its density.

Recrystallization temperature is affected to some extent by the time allowed (Fig. 376) and section thickness. As the temperature is raised above the recrystallization range and into the forging or hot-working range, annealing soon becomes practically spontaneous so that only mechanical considerations (ease and freedom of movement) limit the extent of working. Atomic activity has then reached a point permitting molecular masses to be moved about quite freely although

not yet so fluid (molten) as to flow by gravity. This freedom of molecular rearrangement in the *thermoplastic range* has also been referred to as the amorphous state.

Pressure-welding of powders of thermoplastic materials, both metallic and organic, takes advantage of intermolecular attraction for bonding purposes. Distinction should be noted between such pressure-welding of similar fragments and the bonding of powder mixtures in which some powders are bound together by *other* constituents introduced as adhesives or binders.

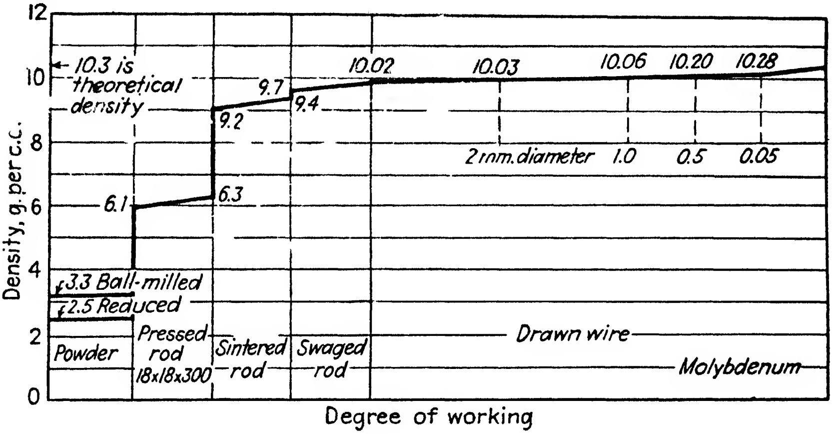


FIG. 377.—Improvement in density as molybdenum powder is cold pressed at 60,000 psi then " sintered " above its recrystallization temperature to permit improvement of inter-atomic relations, then plastically worked by swaging and wire drawing with intermediate annealings to correct inter-atomic strains. (*Courtesy C. G. Goetzel, Amer. Electro Metal Corp. and American Society for Metals.*)

The four essentials of pressure-welding are: *intimate contact* of *clean particles* at *suitable temperatures* within their thermoplastic range and for *sufficient time*, Fig. 376, to permit adjacent atoms or molecules to improve their relative alignment and establish cohesive forces as a bond. Such pressure-welding can occur almost instantly between particles of a steel shaft in a steel bearing or of a steel sheet in a steel draw die when the insulating film of lubricant breaks down. Pressure above the yield point of the material assures intimate contact. Further improvement may be accomplished by mechanical working of the mass, forging granules into even more uniform compactness and filling cavities which molecular or atomic forces could not close. Oxidation of surfaces forms an effective barrier against forming molecular bonds and accordingly a protective atmosphere or enclosure is usually required during the welding or sintering period.

Where porosity is desired the particles need only join at random points of contact. However, voids among the cohesive particles may be reduced by pressure or substantially eliminated by plastic working during or between applications of heat sufficient for recrystallization. As lead and tin recrystallize below atmospheric temperatures, it is reported that their powders may be pressure welded without added heat at pressures down to 500 psi. Tungsten is an outstanding commercial example of converting from powder to practically flawless, ductile wire though temperatures are necessarily extremely high.

TABLE XXIIIa

COPPER AND IRON, FROM POWDERED METALS*

Stages in improvement of properties with experimental alternate compression and recrystallization:

COPPER	Density g./cc.	Brinell Hardness	Ultimate Tensile, psi.	Elongation in 2 In., %
Pressed, at 50 tons/sq. in.	7.47	73	970	0
Sintered, at 1470° F., 8 hr.	7.90	34	16,000	9.5
Re-pressed, at 50 tons/sq. in.	8.39	70	22,200	4.0
Re-sintered, at 1470° F., 8 hr.	8.37	39	25,500	17.0
Cold-rolled, 25% reduction	8.33	97	37,300	4.0
Reannealed, after 25% reduction	8.35	39	17,000	16.5
Cold-rolled, 50% reduction	8.57	109	44,400	2.5
Reannealed, after 50% reduction	8.59	41	24,600	22.0
Cold-rolled, 75% reduction	8.80	117	49,000	1.0
Reannealed, after 75% reduction	8.82	44	32,700	27.5
IRON				
Pressed, at 50 tons/sq. in.	6.23	69	470	0
Sintered at 1830° F., 8 hr.	6.68	47	27,000	10.0
Repressed, at 50 tons/sq. in.	7.27	67	30,500	4.0
Resintered at 1830° F., 8 hr.	7.23	63	34,900	20.5
Cold-rolled, 25% reduction	7.39	107	50,500	2.0
Reannealed, after 25% reduction	7.40	63.5	30,600	15.5
Cold-rolled, 50% reduction	7.67	133	63,000	1.0
Reannealed, after 50% reduction	7.69	68.5	32,800	21.5
Cold-rolled, 75% reduction	7.74	161	77,700	0
Reannealed, after 75% reduction	7.75	68.5	33,800	26.0

* From "Plastic Deformation," C. G. Goetzel, Amer. Electro Metal Corp. in *Powder Metallurgy*, A.S.M., Cleveland, 1942.

Fig. 377 indicates the progressive steps in the conversion of molybdenum powder to drawn wire four times as dense. The density is plotted to show elimination of voids and gradual approach toward perfect atomic packing of the crystal space lattice. Along similar lines and more familiar to sheet-metal workers are the comparisons in Table XXIIIa in which are shown experimental steps and changes of properties in conversion of copper and iron particles to ductile form.

Fig. 378 shows how electron activity and intermolecular ties, changing with temperature, affect the mechanical strength of a typical " pressure-welded " thermoplastic.

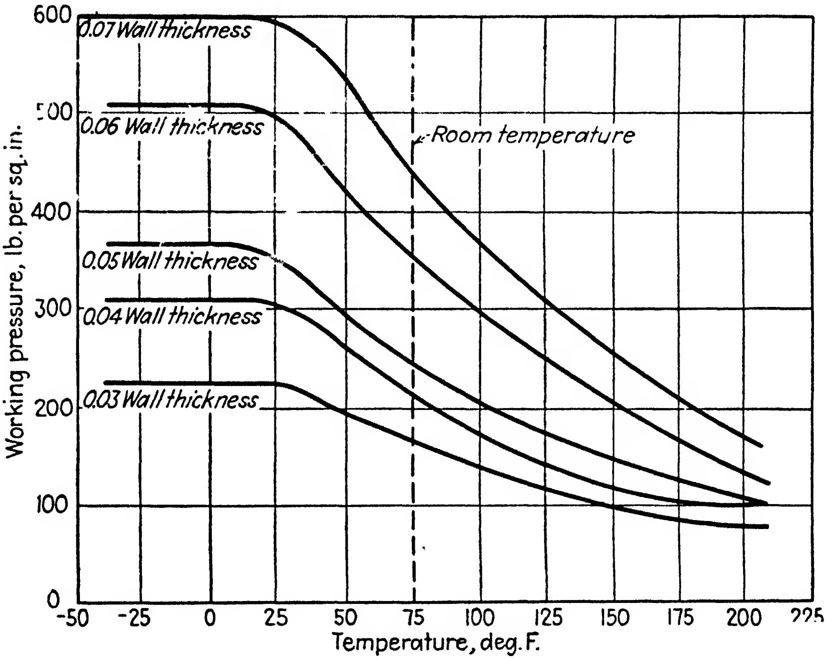


FIG. 378.—As in the metals, strength of vinylidene chloride tubing remains substantially constant in the crystalline state but is reduced with increasing temperature in the amorphous or thermoplastic range. (*Courtesy John Delmonte, Plastic Industries Technical Institute, Machine Design.*)

The material is a synthetic resin, vinylidene chloride polymer, extruded from heated powder and stretched into tubular form. The solidly frozen crystalline state exists below about 30° or 40° F. As the temperature increases, the material becomes softer and more easily changed in shape. Methods of producing the resin permit varying it " from a flexible, moderately soluble material having a softening point of approximately 158° F. to a hard tough

thermoplastic having a softening point of 350° F. or more." Softening points here refer particularly to an approach to fluidity favorable to compression and injection molding.

Creep.—In Fig. 378 compare the range of softening or decreasing strength with the range of increasing creep for the same and other materials in Fig. 379. Here, cantilever beam specimens of several thermoplastic resins and one thermosetting resin, acting as a binder in a fibrous laminating material, were stressed for four days at 1000 lb. per sq. in.

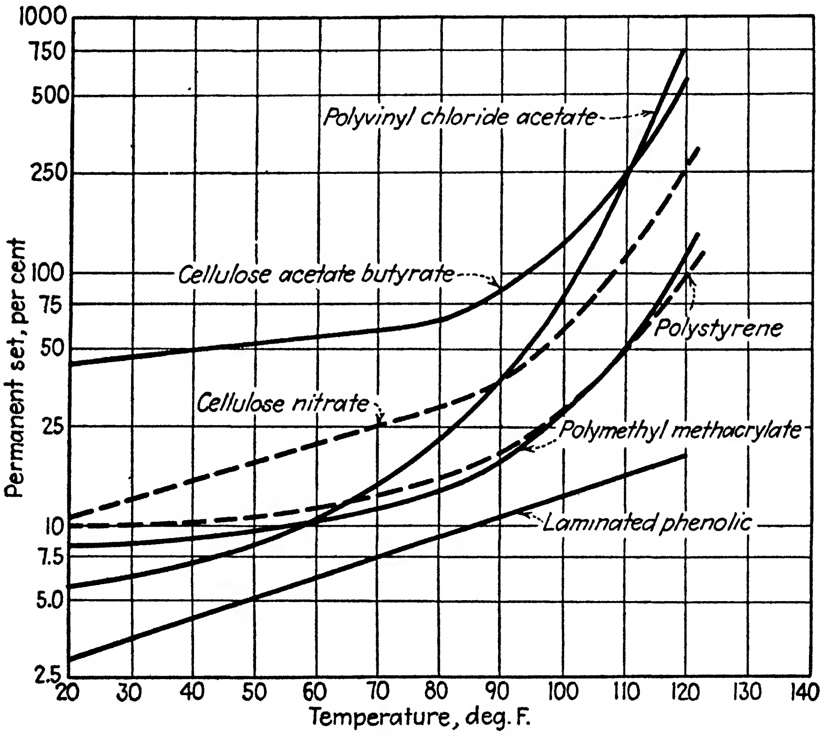


FIG. 379.—Five thermoplastic materials show increasing rate of creep as they pass recrystallization temperatures. The rate remains more constant for thermosetting phenolics up to deterioration temperatures. Load and time were constant. (*Courtesy John Delmonte, Plastic Industries Technical Institute, Machine Design.*)

maximum fiber stress, followed by four days of recovery. Creep and the thermoplastic state are obviously coexistent, for when the intermolecular forces are weakened even in the lower part of the range, a moderate force acting over a sufficient time will gradually cause change of shape in excess of elastic recovery, i.e., permanent set. Lead pipe and lead

roofing creep in the course of years, for lead is also in the lower part of its thermoplastic range at atmospheric temperatures.

Rate of creep in thermosetting materials is more constant (Fig. 379) up to limiting temperatures (about 212° F.). Fig. 380 showing time and creep relations for a laminated phenolic thermosetting material would also seem to indicate an ultimate decrease in the rate of creep. Although this might be traceable in part to taking up slack or better alignment of fiber chains per Fig. 382 and Fig. 383, the coincidence of time at different loads might also suggest a time limit on the stability of the plasticizer used in this mixture.

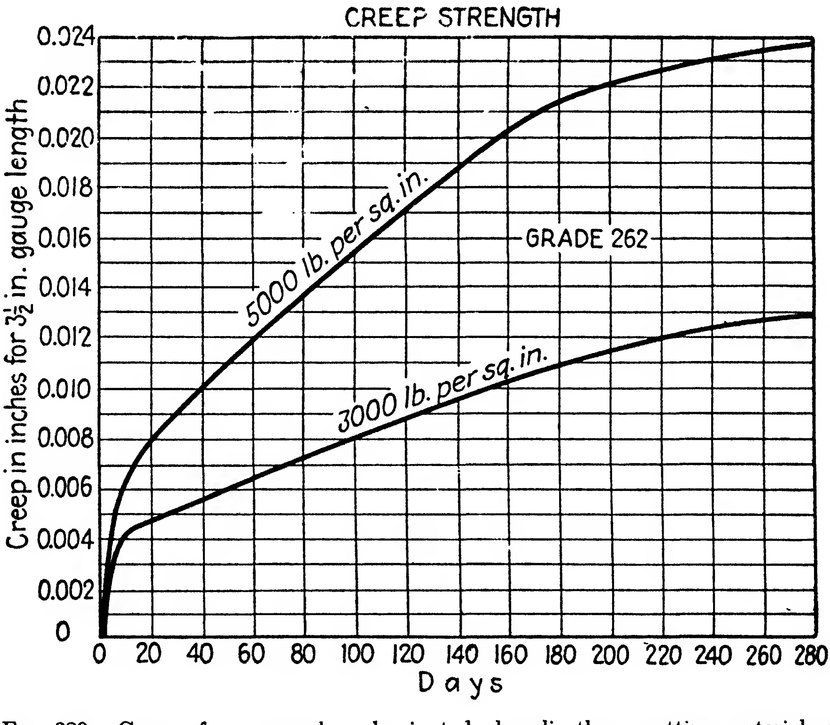


FIG. 380.—Creep of a canvas base laminated phenolic thermosetting material at two different loads. (*Courtesy Westinghouse Electric and Mfg. Co.*)

Speed in Thermoplastic Flow.—Between the solidly frozen crystalline state and the fluid molten state, the flow of thermoplastic materials (metallic or organic) varies from creep, comparable to glacial movement, to the almost turbulent flow of injection molding. In Fig. 381 tests were run at two different testing machine speeds (slow compared to commercial operation) which illustrate effects of speed

upon elongation (see page 209) and upon strength which, of course, is also the resistance the material offers to flowing or changing its shape. Fig. 233 on page 263 shows again that resistance increases with speed in the thermoplastic range up to a certain point. At any particular temperature this variation depends upon the time required to stress-relieve or equalize the bonds between molecules as indicated in Fig. 376. The work done upon these bonds in forced change of shape generates heat in proportion to the speed. Extrusion from a cold slug, of the copper tube at 12, page 247, although unsuccessful at slow speed, works commercially in fast crank presses because sufficient internal heat is

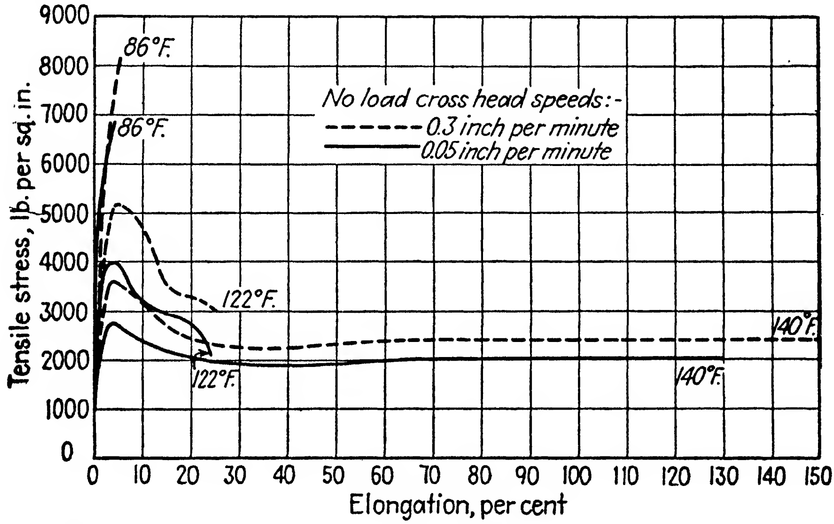
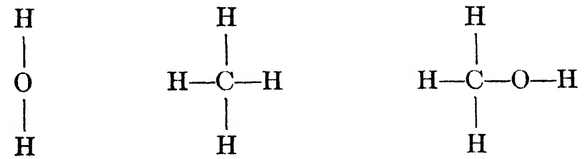


FIG. 381.—At temperatures within the thermoplastic range (of methyl methacrylate) increased testing speed results in higher yield point, greater resistance to plastic flow, and greater elongation to point of fracture. From DuPont " Lucite " data.

generated to correct interatomic strains and turn out substantially annealed material despite about 1000 per cent elongation. Speed is also essential in many hot-forging and plastic-forming operations, as of Lucite bomber nose sections, to complete the operation before the blank chills. In other cases toward the lower end of the plastic temperature range, speeds of severe forming operations may have to be reduced to avoid fracture by permitting stress-relief to keep up with the strain applied.

Polymers.—The organic chemistry of synthetic resins is interesting in the multiplicity of ways in which a few elements, principally carbon, hydrogen and oxygen can be put together into different molecules, strings of molecules and mixtures of molecules. Of the three most

common elements, an atom of carbon may be represented as holding out four hands to grip desirable associates, whereas hydrogen has only one hand and oxygen two. Thus molecules of water (H_2O), methane or marsh gas (CH_4) and methanol or wood alcohol (CH_3OH) may be represented respectively:



All these are satisfied atoms having no unoccupied hands. However, as the combinations become more and more complex some are found among the synthetic plastics which leave an unoccupied hand extending here and there for chemical attachment to reasonably attractive adjacent molecules. The methods of inducing molecules to string together, thus in chain form, has been christened polymerization. It is a great help in developing properties suitable to tubes, threads and rubbers. The natural rubber molecule, C_5H_8 or isoprene, clasps hands in polymer groups of up to 4000 molecules, and the larger the group, the more elastic is the material.

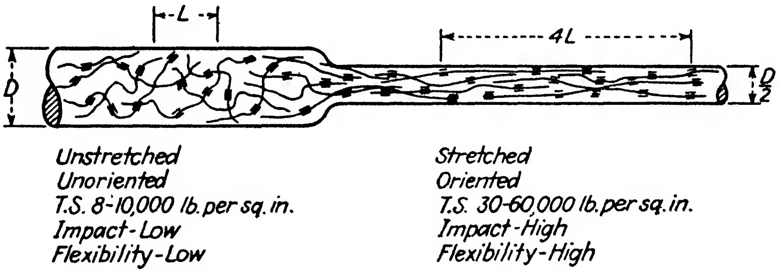


FIG. 382.—Diagrammatic representation of orientation by mechanical working of molecule chains of polymerized vinylidene chloride. (*Courtesy W. C. Goggin, R. D. Lowry, The Dow Chemical Co.*)

Oriented Polymers.—By the mechanical stretching, rolling or other directional working of materials made up of groups of such chains of molecules, the mechanical properties are advantageously affected as in the production of Nylon thread. Interesting illustrations of vinylidene chloride polymers presented by Goggin and Lowry[1] are shown in Fig. 382 to 384. In Fig. 382 they indicate that the lining up or orientation of

[1] "Vinylidene Chloride Polymers," W. C. Goggin and R. D. Lowry, American Chemical Society, March 18, 1942.

chains accomplished by a 400 per cent elongation or equivalent 80 per cent reduction in area increased the tensile strength of the material in the neighborhood of 400 or 500 per cent. Fig. 383 represents the increase of strength of small section filaments as they are stretched. Comparison of the sharp rise at the end of the curve with those for copper, Fig. 123, and for aluminum, Fig. 124, suggests strain-hardening in the mechanical working of the oriented crystal chains.

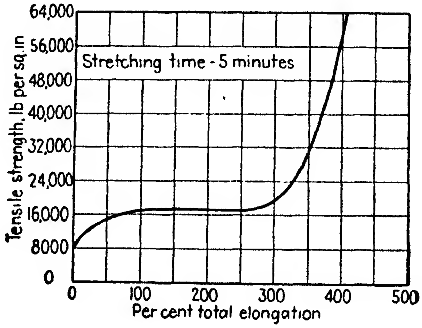


FIG. 383.—The stress-strain relation, accompanying Fig. 382 for Saran monofilaments, probably represents chain alignment during the horizontal portion and strain hardening as in the metals, during the subsequent rise. (Chart, *courtesy W. C. Goggin, R. D. Lowry, The Dow Chemical Co.*)

X-ray diffraction studies of Saran, Fig. 384, show at *A* the random light distribution of the material in the amorphous or thermoplastic state, at *B* the ring distribution of the general crystal structure and at *C* the crystal pattern of the oriented structure. In connection with these illustrations of increasing directional strength by orientation, it is interesting to refer to metals again. As was pointed out in Chapter II, the force to pull two atoms or molecules directly apart is far higher than familiar tensile strengths, whereas the force to cause diagonal slippage along planes of weakness between layers of atoms in orderly crystal pattern becomes less and less, as boundary interferences are eliminated. Thus, a ½-in. bar of copper annealed to the state of a single crystal may be bent in the two hands. But, cold-worked to the upper end of its plastic range, its yield point rises above 60,000 or 70,000 lb. per sq. in. A 0.15 C steel with an annealed yield point of 55,000 psi. or less may be cold-worked to a yield point over 110,000 psi. In wire drawing such a steel, Table XVIII, the directional working, in the presence of work generated heat (which may readily bring the whole small section up into the thermoplastic recrystallization range) apparently results in a combination of preferred orientation and strain harden-

ing, bringing the tensile strength (and yield point) up in the neighborhood of 250,000 psi.

Among engineering materials it seems wise to distinguish the half dozen states of internal bonding with which we must deal: pure *elements*, such as iron (Fe), copper (Cu), carbon (C), oxygen (O); uniform *compounds* made up of atoms of two or more elements fixed in definite ratio such as iron carbide (Fe_3C), water (H_2O), sulphuric acid (H_2SO_4); *variable compounds*, such as the phenolics, cellulose acetates and other synthetic resins, in which properties may be varied appreciably by developing in varied proportion two or more closely related complex molecules made up in similar ways from the same elements like cellulose triacetate $C_6H_7O_2$ $(COOCH_3)_3$ and cellulose tetra-acetate C_6H_6O $(COOCH_3)_4$; *solutions of elements*, such as the brasses, in which various proportions of zinc atoms (Zn) disperse amongst copper atoms (Cu); *solutions of compounds*, such as salt (NaCl) dispersed in water (H_2O), water in cellulose acetate or phenolics in alcohol; increasingly important *mixtures* or alloys or trade name recipes, which combine elements, compounds and/or solutions, often limited in proportion by mechanical, rather than chemical considerations.

Mixtures.—From familiar clam chowder to alloy iron castings, useful mixtures take on characteristics of their components and even assume characteristics desirable beyond any of their components. Modern engineering materials have assumed variety often more intricate than clam chowder.

Cast iron is a mixture typical of the varied possibilities which the name implies. Many recipes are cooked up, containing various proportions of ferrite, atoms of pure ductile iron, Fe; molecules of iron carbide, Fe_3C, a hard, brittle compound known also as cementite; pearlite which is a solid solution of iron carbide in iron; free carbon or graphite; plus pinches of sulphur, phosphorus, silicon and possibly chrome carbides and nickel. Like the "organic plastics," the properties of this mix vary widely according to the requirements and the skill of the cook. Tensile strength ranges from 10,000 psi. for a sash weight iron to 80,000 psi. for a heat-treated crankshaft iron. Compressive strengths may run to double or more which is quite characteristic of mixtures, whether they are organic, ceramic, metallic or what-not. Perhaps we may let it go for the moment that the color pigments, plasticizers, economy fillers, hardening and reenforcing agents which often go into mixtures, may cooperate successfully with binders or adhesive components in compression, but are unlikely to do so efficiently in tension.

Organic, *ceramic* and *metallic* groupings of engineering materials are not the arbitrary divisions they seem to be at first. The same common

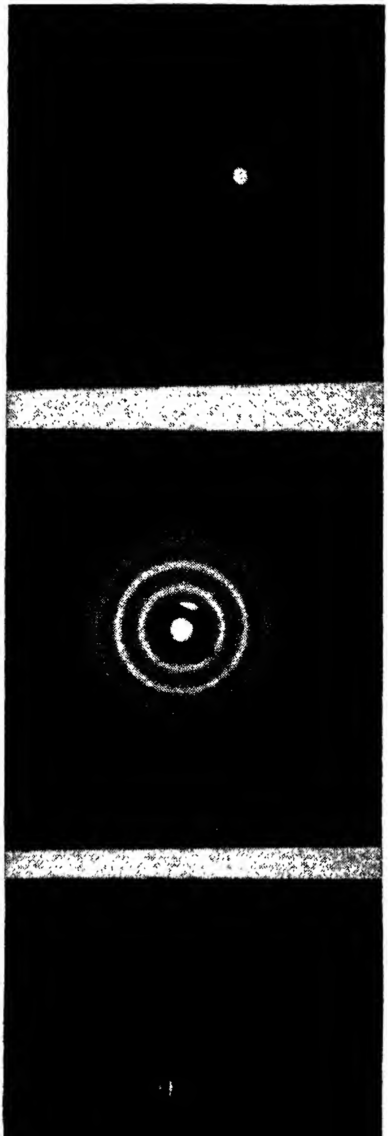


FIG. 384.—X-ray diffraction photos of: *A*, amorphous Saran; *B*, crystalline Saran; *C*, oriented crystalline Saran. (*Courtesy W. C. Goggin, R. D. Lowry, The Dow Chemical Co.*)

elements bob up here and there all through them. Carbon which may be soft as smoke or hard as a diamond, forms nearly 90 per cent of the molecular weight of rubber, C_5H_8. It becomes transparent as a large component of Lucite, Lumarith, Cellophane and others which stem from wood, cotton and coal. Among the hard synthetic cutting tool and die materials, it appears frequently both as carbides among the hard fillers and in the soft to brittle binders or adhesives. Aluminum, a metallic element, is compounded naturally in clay and rubies. It reappears alone or with oxygen or other flavorings, as planes, pots, dishes, tiles, glass and carborundum all of which have in common that they may be mass produced for the mass welfare with machine push and heat.

The chemistry of all these things can become quite complicated, but as their chemistry is usually not essential to the actual working of the expanding realm of engineering materials, the effort has been to give only enough of the basic chemical data for an appreciation of the groupings. The suppliers of the pig, sheet and powdered materials can furnish up-to-date physical data, etc., on their various compounds and alloys. Some data is listed in Table XXVII*b* and *c* in the Appendix, but this is necessarily subject to alteration and expansion.

Table XXIII*b* lists a few of the alloying ingredients of commercially useful engineering materials. Instead of the elements and simple compounds which are combined to make up most metallic alloys and mixtures, we may start with complex materials for which it is not yet feasible to write a chemical formula. The arbitrary division of fillers, adhesive agents and lubricants and their subdivisions may be indefinite and overlapping in spots and the same elements may recur here and there in different combinations. Chemical research has shown thousands of possible combinations and commercial practice has found hundreds of these to be competitively useful. Changing relative material costs, heating costs and handling costs in conversion to satisfactory shapes determine selections which are, therefore, also subject to frequent change. A few more typical mixtures may be of interest before going into grouping the methods of conversion.

Cements.—That general term has come to cover a variety of adhesives familiar to the layman by function. Their natural ancestry goes back to the clay-bearing muds and natural plasters which were reenforced with twigs or straw for pagan mansions. Ordinary white plaster on our walls is an interesting and chemically simple solusetting compound:

$$CaO + H_2O = Ca(OH)_2$$

TABLE XXIIIb

SOME COMPONENTS OF SYNTHETIC MIXTURES

FILLERS

FOR BULK
- Wood pulp
- Wood flour
- Asbestos
- Marble flour
- Sand
- Gravel
- Macerated cloth
- Mica
- Jute
- Kapok
- Hemp (sisal)
- Flax
- Ground cork
- Powdered rubber
- Lead (powdered)
- Cotton flock
- Walnut shell flour
- Soybean meal

FOR REENFORCEMENT
- Wood plys
- Papers
- Fabrics (strip, macerated)
- Metal rods
- Metal mesh
- Glass fabric
- Straw, etc.
- Rayon
- Asbestos
- Felt

FOR HARDNESS
- Iron carbide
- Chrome carbide
- Tungsten carbide
- Tantalum carbide
- Titanium carbide
- Iron nitride
- Chrome nitride
- Vanadium nitride
- Carborundum
- Alundum
- Crystolon

HEAT, WATER OR CHEMICAL RESISTANCE
- Asbestos
- Graphite
- Tungsten
- Slate flour
- Mica
- Whiting (calcium carbonate)
- Barytes (barium sulphate)
- Diatomaceous silica

FOR APPEARANCE
- Metallic pigments
- Powdered copper
- Powdered aluminum
- Zinc oxide
- Calcium sulphide (fluorescent)
- Lithopone
- Organic pigments

ADHESIVES

THERMOSETTING
- Phenol-formaldehyde
- Urea-formaldehyde
- Melamine-formaldehyde
- Aniline-formaldehyde
- Casein-formaldehyde
- Phenol-furfural
- Phenol-lignin
- Columbia resin 39
- Rubber — sulphur
- Shellac
- Copper — tin } in powder metals
- Copper — iron } in powder metals

THERMOPLASTIC
- Phenol-acetone
- Cellulose acetate
- Cellulose nitrate
- Ethyl cellulose
- Cellulose acetate butyrate
- Methyl-methacrylate
- Acrylic
- Vinyl acetate

THERMOPLASTIC (Continued)
- Vinylidene chloride
- Styrene { Vinyl chloride
- Styrene { Vinyl acetate
- Asphaltum
- Gilsonite
- Cobalt } as binders for carbides, etc.
- Iron } as binders for carbides, etc.
- Copper } as binders for carbides, etc.
- Glue (hide)

SOLUSETTING
- Plaster
- Cement
- Paint oils (for pigments)

SOLUPLASTIC
- Most thermoplastic and thermosetting resins (especially prior to setting) are soluble in various chemicals.
- Casein
- Magnesium sulphite
- Calcium sulphite

TABLE XXIIIb (*Continued*)

PLASTICIZERS

(intermollecular or intergranular)

FOR FLOW LUBRICATION IN MOLDING, FOR FLEXIBILITY IN SHEETS

Water (in most paper)	Theop
Glycerol	Santicizer M–17
Castor oil	Diethylene glycol dipropionate (KP–45)
Tung oil	Diethylene phthalate
Waxes	Dimethyl phthalate
Opalwax #10	Tripropionate
Dibutyl phthalate	Triacetin
Diethyl phthalate	Triethyl citrate
Diotvl phthalate	Dibutyl tartrate
Tricresyl phosphate	Talc
Monophenyl phosphate	Sterate of zinc
Chlorinated diphenyl	Graphite
Fractol A	Sericite
Flexol 3GH	

Lime + water = calcium hydroxide, which is not yet plaster, but it is the workable or moldable state in which it is troweled up on the walls. There it " sets " by reason of a chemical change which requires taking in carbon dioxide, CO_2, from the surrounding air and dissipating moisture, H_2O, to the air:

$$\begin{array}{ccccc} Ca(OH)_2 & + & CO_2 & = & CaCO_3 + H_2O \\ \text{Calcium hydroxide} & + & \text{carbon dioxide} & = & \text{plaster} + \text{moisture} \end{array}$$

The builder's bonfire is needed both to bolster the supply of CO_2 and to help dry out the moisture. Natural plaster is the chalk of the white cliffs of Dover. When lime is mixed with asbestos, which is aluminum magnesium silicate, water is added to make plaster the adhesive in a furnace-coating material.

Concrete is a typical useful *solusetting mixture.* Substantial proportions of sand and stones serve as fillers which are cheap and strong in compression. Steel bars are added, as reenforcement, in suitable positions where tensile strength must be considerable. The adhesive " cement " is cooked up from suitable natural rock deposits and is in itself a mixture of several elements which " set," in a reaction typified by that of plaster, but complicated by variety so that it is doubtful if the chemists could write down just what does happen. Powdered iron, copper and aluminum are used in concrete for various special purposes. The aluminum powder with slightly alkaline water is said to generate hydrogen and form a light insulating sponge-concrete. The cheaper color pigments such as carbon black and metal oxide earths may also be included.

The mixtures which follow are characterized by fillers which feature *hardness* for cutting qualities or for heavy-duty dies. Thus, for abrasive cutting, hard crystalline particles of Carborundum brand or Crystolon brand, silicon carbide are commercially bound together with such varied adhesive agents as rubber, phenolic resins, ceramic clays or

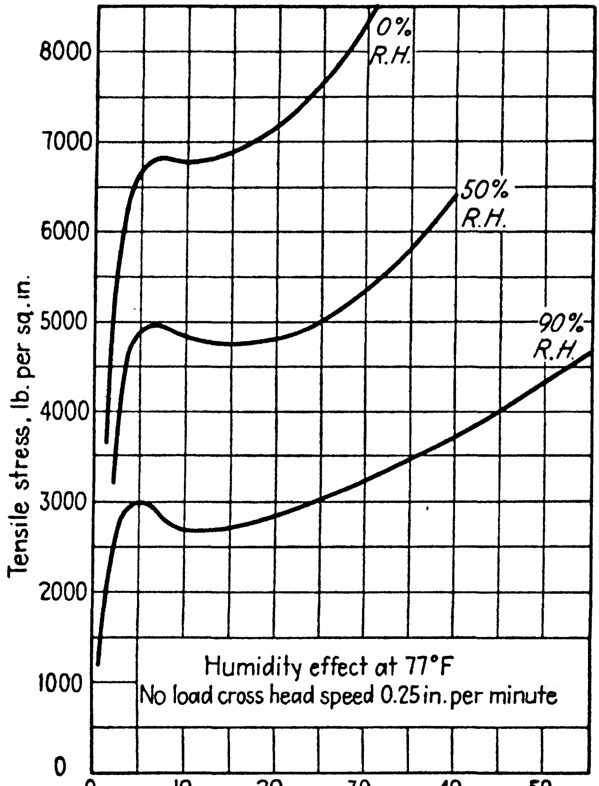


FIG. 385.—As the proportion of water molecules dispersed among cellulose acetate molecules increases toward saturation, the plasticizing effect reduces the resistance to plastic flow and increases the plastic range. (*Courtesy Celanese Celluloid Corp.*)

shellac which is a resinous insect secretion. Tool steels might be described as hard iron carbide, chrome carbide and possibly others in a matrix of iron as the adhesive. A species of thermosetting reaction, familiar as Nitriding, produces hard surfaces of iron nitride, chrome nitride and vanadium nitride by "mixing" nitrogen gas and chrome vanadium steel at suitable temperatures. Hard tungsten carbide,

tantalum carbide or titanium carbide with up to 20 per cent of cobalt as the binder will stand exceptional cutting pressures or compressive loads, but have their shortcomings in tension. Cold-forging and heading dies made from them require shrunk steel bands or other preloaded reenforcing members to protect them from tensile failure. The foregoing mixtures are pressed to shape from powder form and then sintered (baked at suitable heats) to plasticize or set the binder.

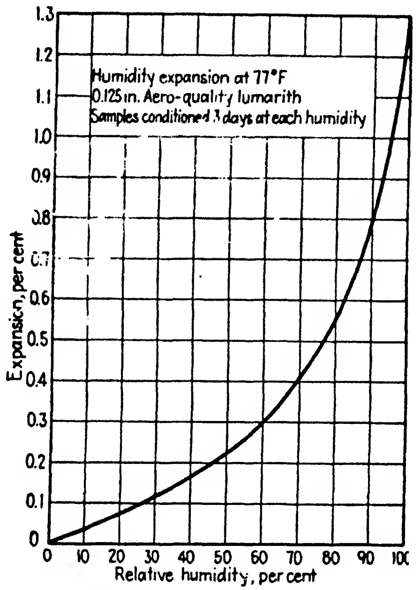


FIG. 386.—Change in dimension between dry and water-immersed Lumarith indicates the small amount by volume of water which goes into solution at saturation. (*Courtesy Celanese Celluloid Corp.*)

Papers are mixtures with widely contrasting properties to those just mentioned. They are of interest because pressure and dies are used more and more to cut and form them into useful shapes. In many applications, papers of varying quality and possibly cross-creped or gathered to improve their forming range, serve as the reenforcing medium, with or without other filler in many " laminated " sheets and shapes with phenolic, urea or melamine thermosetting resins as binders or glues. Paper is likely to be a mixture of organic and inorganic, vegetable, mineral and synthetic constituents. It starts, as a rule, with a suitable wood pulp broken down into clean cellulose fibers and mixed with water-soluble adhesive agents which may also serve as a size to offset absorbent tendencies; and be further mixed, impregnated

or coated with thermosetting or thermoplastic adhesives, coloring matter, surface coatings and plasticizing or waterproofing waxes. The added materials may include starch, casein, various clays, bleaching powder, barium sulphate (to fix whiteness), asphaltum, alum, animal glues, natural rosin and various synthetic plastics. Thus, the elements in paper may be C, H, O, Ca, B, Cl, Ba, Al, etc., indicating the possible

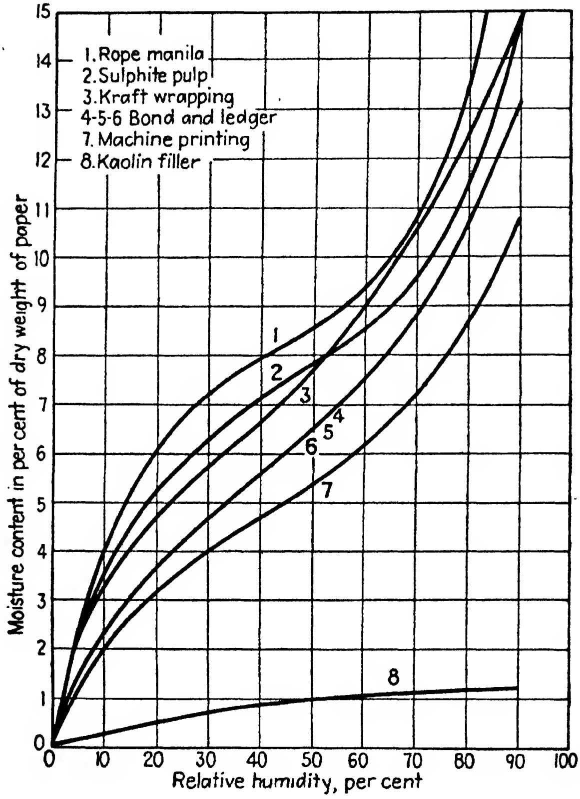


FIG. 387.—Variation of moisture content by weight in several different papers as relative humidity varies from dry to nearly saturated. (*Courtesy The Foxboro Co.*)

complexity of reactions. Depending upon the choice of constituents in the mixture, paper may combine properties so that it is both soluplastic and thermosetting. This combination permits softening the soluble binder in the paper or layers of paper with a proper proportion of moisture to permit stretching or forming to the desired shape, then curing at sufficient temperature to dry and to set the resinous binder, and under sufficient pressure, to assure intimate contact of layers.

Plasticizers.—In mixtures, plasticizers, such as those listed in Table XXIII*b*, might be described as integral or internal lubricants. *In powder mixtures*, they give greater mobility and easier flow through passageways and molds. For use with ethyl cellulose one authority recommends that a plasticizer be added in the proportion of 10 to 20

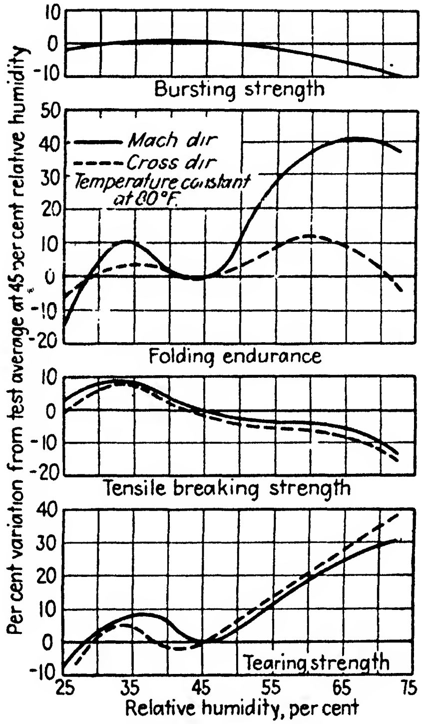


FIG. 388.—The effect of the plasticizer upon the binder through a part of the relative humidity range is reflected in varying comparative properties of a paper. (*Courtesy The Foxboro Co.*)

per cent for compression molding, 15 to 30 per cent for injection molding and 25 to 50 per cent for extrusion mixtures. *In sheet materials*, about 5 per cent by weight of water in paper keeps water-soluble binders soft enough to avoid brittleness. Cellophane, a cellulose sheet, which would tend to brittleness if dried, is dipped in glycerol, absorbing up to 7 per cent of it for flexibility and holding it in a solution relation of spaced molecules. Water also goes "into solution" in some of the thermoplastics improving their plasticity as indicated by elongation and, reducing their resistance and elastic limit at the given temperature as shown in Fig. 385. Expansion of the cellulose acetate as water

goes into solution in it from minimum to maximum content, is shown in Fig. 386. Even at 100 per cent R. H. (relative humidity) the total amount of water which will dissolve or disperse in cellulose acetate is small, but in view of the great difference in molecular weights the ratio in molecules of each at saturation is not so low. That is, there may be one of water spaced among four or five molecules of cellulose acetate. The effects of this inclusion or solution of a fluid compound in or dispersed through the structure of a less mobile material may help in visualizing the function of the plasticizer.

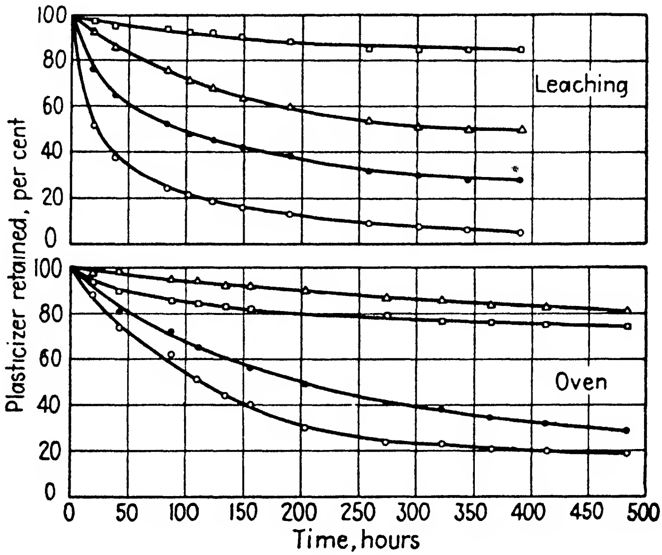


FIG. 389.—Loss or dissipation of several plasticizers out of combination with compression molded plastics: upper curves show percentage loss by leaching or dissolving into surrounding water at 104° F.; lower curves show loss by evaporation into air, accelerated at 149° F. Plasticizers tested: open circles, dibutoxyethyl succinate in vinyl chloride acetate copolymer (87%); filled circles, same in polyvinyl butyral; triangles, dibutoxyethyl fumarate in polyvinyl butyral; squares, glycidyl esters of babassu oil in polyvinyl butyral. (*Courtesy U. S. Western Regional Research Laboratory.*)

Although water is the vital plasticizer in most papers, Fig. 387 (and wood), it is erratic in its tendency to evaporate and dissipate or return as the relative humidity of the surrounding atmosphere decreases or increases. It is easy to make a paper brittle by over-drying, Fig. 388 but it is more difficult to restore pliancy throughout the paper. Perhaps this is because to get H_2O molecules into the inner structure it would be necessary to use so much moisture on the surface as to dissolve out

fillers and binders among the surface fiber chains. Absorption and dissipation of atmospheric moisture by many mixtures has a sometimes troublesome tendency to carry off small amounts of soluble plasticizers and binders.

Among " plastics " (synthetic woods) water is generally an incidental and uninvited plasticizer, and in a few cases is not taken up at all. Alternatives include certain oils, talcs, waxes and their chemical equivalents as suggested in Table XXIII*b*. The ideally stable plasticizer, Fig. 389 would be unaffected by atmospheric or molding temperatures or by oxidization, or otherwise subject to dissipation or disintegration due to acids, alkalies or other materials with which it may come in contact. The chemical reactions of the constituents of any composite material with its surroundings promises to continue to be a major problem for the chemists. Referring to the use of molded plastics in contact with various liquids or pastes a leading molder warns, " Although the general effects of the better known reagents on the molded materials are given, it is surprising and at times embarrassing to see the havoc that can be created when a seemingly innocent little stranger slips into the contacting material."

Pressure Forming.—This is the economical mass production method and now appears applicable to a tremendous variety of elements and combinations of elements in the expanding picture of engineering materials. As the fundamentals of many arts become common knowledge, it develops that a comparatively few basic working principles apply whether the materials are ceramic clays, glasses, plasters; organic woods, fibers, rubbers, synthetic resins; metals new and old in whatever form; or the various intercombinations of these several groups. The presentation of compositions, physical properties and temperature-pressure relations in the several states of plasticity and fluidity attempted in the Appendix, Tables XXVII*a*, *b*, and *c*, shows many present gaps. As the data accumulates, however, the methods of economically moving the material into required shapes need offer no great difficulty.

CHAPTER XVII

MOLDING AND FORMING

The list of materials, both simple and complex, which are presently passing through their chemical and physical adolescence into utilizable engineering materials, reduces those which were familiar at the turn of the century, at least to a numerical insignificance. The most complex are nature's recipes, the wood, stone and clay which have been whittled, pounded or molded to useful shape by rule-of-thumb methods through the ages. The newest are the synthetic alloys and mixtures which, by the substitution of orderly science for art, have been made available and tractable for the greatest good of the greatest number. As the fog of experimental manufacture lifts from each usable arrival, it is found to be formable by the orderly application of natures own routine, i.e., temperature, pressure and time. Hence, it seems worth while to note what may be involved in varied combinations of *form* with *temperature, pressure* and *time.*

Form implies some combination of usage, art and purpose. For manufacturing purposes the form must be translated to suitable engineering dimensions, and thence to " tools " (molds, dies or rolls) suitable for reproduction of the form or part in the selected material. As compared with common knowledge of casting, primarily in molds made of sand and clay, and of forming, primarily in dies and rolls made of hardened steels, we now find a diverse choice and usage of tool materials ranging from confined steam, water and rubber to plastics, plasters, wood, cast, rolled and powdered metals, and on to sintered carbides reenforced with prestressed alloy steels. Governed always by comparison of costs of tool material and tool fabrication with useful tool life, the material must be capable of standing the temperatures and pressures involved. Furthermore, it should be of a sufficiently dissimilar nature to the material being formed to avoid galling (pressure-welding or intermolecular cohesion).

Temperature required in manufacturing processes may vary from subzero, as in forming cakes of carbon dioxide ice, to that of the electric arc, as in producing synthetic abrasives. Temperature must often be controlled within rather narrow limits for success. Several general temperature ranges should be recognized:

Crystalline range, in which the material is frozen or set in its crystal pattern, although that arrangement may be disturbed by pressure working if the pattern is sufficiently simple to allow crystoplastic forming.

Recrystallization range in which electron activity becomes sufficient for atomic or molecular readjustment, as in stress relieving and annealing.

Thermoplastic range from recrystallization to fluidity, in which a thermoplastic material may be moved about more freely as temperature rises, within purely mechanical limits of movements.

Fluid range, as for casting purposes, in which interatomic or intermolecular bonds are rendered transient by heat or solvent.

Gaseous range in which atoms and molecules space themselves quite independently. (This also enters in soluplastic and solusetting processes where a liquid solvent must be evaporated or "dried out.")

Heat treating range in which dispersion hardening or suitable crystal grain size is established.

Thermosetting range of certain mixtures in which chemical change of adhesive constituents takes place at prescribed temperature. In most if not all these, the temperature range limits are subject to variation with internal stresses or external pressures.

In that the mercenary commercial aspect of relative expense governs the success of competitive enterprise, investment and operating charges receive primary consideration at every step. Heating equipment cost, fuel charges, hot handling charges, temperature control, cooling costs, atmosphere control, cleaning, washing and drying costs are frequently substantial items whether process temperatures are high or low.

Pressures may vary from a near vacuum, used in distributing from solution, as in paper making and screen molding, to a hundred or more tons per square inch, in severe extrusion and cold-forging operations. Increasing flow speeds, greater restrictions to flow, more viscous or tougher materials, more severe restrictions on cavitation and entrained gas flaws, and closer tolerances on finished parts require ever more powerful and more rigid machinery to cope with conditions.

Time is the fourth ingredient in manufacturing recipes and "the fourth dimension" on the process chart. Sufficient of it must be expended to complete precisely the feeding, heating, stress relieving, chemical reaction, drying, discharging or whatever the step may be. In every case, time is distinctly money. The synthetic plastics, for example, have been distinctly handicapped competitively in their initial development, by the time required in expensive equipment to complete

the transmission of heat and the chemical change to set, or to complete, the relief of intermolecular strains. The reduction of time per unit, by larger quantities in process and more efficient processing equipment, is the essence of American mass production.

Plastic working, first of metals and now of many more materials, seems properly limited to the several plastic states (Chapter XVI). Indulgence is requested, however, for some consideration of the fluid state (casting). Assembly operations, such as the laying together of a stone wall, the building of a house or the fitting and fastening together of an airplane, are not a part of this discussion. Neither are the whittling, scraping or rubbing (machine tool and grinder) operations which precede assembly to correct inaccuracies and assure fits.

Casting, or the pouring of a fluid material into a suitable mold to harden or set is simple but may readily be quite troublesome. Tendencies are common to shrink, to entrap air bubbles, to produce gas bubbles or shrinkage voids, to crystallize or set non-uniformly with internal strains, to erode the mold and pick up dirt or impurities, to segregate, in the case of mixtures, giving non-uniform chemical and physical properties.

Solvents, such as water, oils, alcohols, esters, etc., render many materials and mixtures fluid for casting. All require considerable time and possibly heat for drying, and the more expensive solvents must be recovered for economy. Concrete is poured in earth, wood and metal molds. Magnesite building materials may also be poured in laminated plastic molds with rubber cores for easier stripping. Wood pulp, wood flour or other organic fibers with suitable binders may be cast in screen molds with the aid of air pressure or suction as in papier-mâché and similar work or progressively on screen belts or rolls as in starting paper, felt and synthetic board manufacture.

Heat is expended to melt to fluidity many materials extending from the waxes and resins to the glasses and steels, each in its turn representing a wide variety of chemical analyses. Casting like molding, which follows, deals with organic, synthetic, ceramic and metallic materials, reminding us of the scope of the present engineering outlook. In addition to casting troubles already noted, the tendency of many hot materials to unite detrimentally with oxygen must be met frequently. A brief review of common casting methods may prove helpful for the light such review may throw upon subsequent discussions.

Molds for casting iron, etc., are ordinarily made of clean sands selected for grain shape and size (to assure gas venting), bonded with small amounts of clays of sufficient heat-resistant capacity for the high temperatures involved and probably reenforced with rods, wires, nails,

etc., to withstand stress and erosion. While originally shaped by hand, and later, with tools and sweeps, present practice requires a pattern formed to the shape required. It is built into the mold in such a way that the mold may be separated in two or more parts to successfully remove the pattern and to insert baked sand and clay cores thus leaving a cavity of just the shape of the piece required but just enough larger to allow for shrinkage. As production and precision demands increase, pattern materials vary from soft woods, hard woods, plaster of Paris and possibly plastics to single and multiple metal patterns arranged for rapid reproduction of sand molds with mechanical assistance. For brass and bronze castings semi-permanent plaster molds helped to reduce mold cost per piece. Next metal molds and machine handling methods made production history in the manufacture of articles from molten glass.

Die casting combined long-life metal molds, mechanical mold closing and holding, molten metal injection and final stripping of the chilled casting. It was another forward stride in mass production of accurate castings. Tool steel dies worked well for the low-melting-point " white metal " alloys of lead, antimony, tin, zinc and later aluminum. Soon thereafter the more heat-resistant die alloys made possible the die casting of higher-melting-point brasses and bronzes.

Injection molding applied much of the machinery and technique of die casting to the production of parts made from synthetic resins or other adhesives and their mixtures. As in Fig. 390, the powder mix prepared to suitable granule size (3⁄16 in. to 5⁄16 in. for tenite, a cellulose acetate or cellulose acetate butyrate) is delivered from a hopper in measured volume to the path of the injection plunger which forces the charge through the heating chamber and into the die cavity from which the finished part is ejected as the die opens. Production cycles are governed by the time needed for application and dissipation of heat to suit the particular mixture and to permit possible die cleaning and application of inserts. Tables XXVII*b* and XXVII*c* in the Appendix give data available for typical materials.

Injection pressures necessarily vary both with the interference to flow of narrow and intricate passageways, and with the viscosity or fluidity through changing temperatures of various proportions of the many resins, flow aiding plasticizers and possible pigments and fillers. The chemical companies advise pressures of 2000 to 50,000 psi. for their various combinations, and long or thin die passageways may raise the requirement to 100,000 psi. or more. For this reason some machines have provision to change pistons and piston sleeves and all permit pressure control. *Holding pressures* should be figured around 50 to 90 per

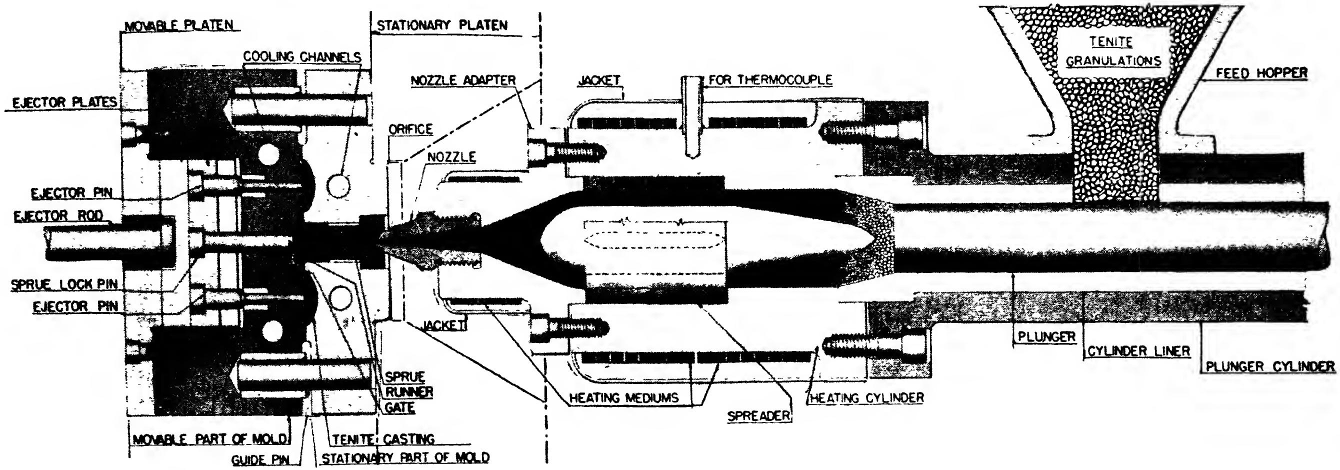


Fig. 390.—A typical mold (die) and heating chamber (for a thermoplastic). The balance of the injection molding machine includes pressure means on the one side for closing and holding the mold, and on the other, for forcing a heated charge into the mold, together with adjusting and cycle control means. (*Courtesy Tennessee Eastman Corp.*)

cent of the product of injection pressure and projected area of the die, since considerable pressure is lost driving viscous material rapidly through the constrictions of the heating chamber and nozzle, but the pressure holding the die closed must be on the safe side to insure against flash.

Heat and time cycle relations in injection molding depend upon whether the material to be handled is thermoplastic or thermosetting. They depend to a lesser extent upon the heat range of the binder and that of the plasticizer, and the proportioning of the die sections.

Thermoplastic materials may be heated and reheated so that they need not rush too fast through the heating chamber, and their scrap gates, sprues and trimmings may be regranulated and used again. Since they are poor conductors of heat they must be separated through passages of small cross-section, Fig. 390, to get the heat into them. The walls of such a heating chamber, are hotter than the material so that a halt in machine operation requires that heating be stopped or overheated material be ejected before resuming operation. Thus a cellulose ester plastic which should be injected at 385° F. might require a cylinder wall temperature of 420° F., but standing at that temperature for 15 minutes would be likely to cause darkening or charring. At a normal cycle of perhaps 4 to 6 injections per minute there would be no danger of overheating. Again owing to slow heat transmission, the molded part might be too soft to be ejected without damage, unless the die were cooled to some extent (say 100 to 200° F., depending upon the resin and plasticizer). For this reason such materials are sometimes confusingly called "cold-setting." Too low a die temperature will cause improper filling or internal strains and strain markings in the material so that dies must sometimes be warmed to start off. Fig. 376 suggests the temperature-time relationship necessary for a material in its thermoplastic state to stress-relieve and readjust its molecular structure to its new shape before chilling. Thermoplastic material then, must arrive in the die cavity hot enough and stay there long enough to stress-relieve and incidentally long enough so that it cools sufficiently to resist a bump on ejection.

Thermosetting materials may be injection molded by heating the individual charge very quickly (by induction or dielectric heating) and getting it right into a hot die to take shape and to hold long enough at the heat to polymerize and/or set. Owing to the chemical change which takes place when the temperature reaches a proper pitch for molecular combination of the resin constituents, the scrap sprues and gates cannot be salvaged. The hardening in hot setting is ordinarily sufficient to permit safe ejection without cooling.

Dies or *molds*, Fig. 390, are leaning toward well-known die set construction with guide pins for convenience in set-up. Sprues are tapered for stripping and a cavity is furnished opposite the sprue to take the chilled slug from the end of the nozzle. This cavity is located so the defective material can be trimmed off to avoid damage to the appearance of the part. Knockouts must be substantially backed to hold flush under pressure. Gates in multiple mold dies, must not be so small as to restrict a quick fill. Passages are usually required to permit cooling dies for thermoplastics or heating those for thermosetting materials. Venting especially at the point farthest from the entrance must be provided to avoid incomplete fills and charring due to trapped air and steam. The latter may also cause sub-surface markings so that precautions are essential to keep powders from taking up atmospheric moisture. Vents often need be little more than a scratch or at most a 0.025-in. hole, tapered out.

The land or area of contact between halves of the die around the profile of the mold or molds and gates should be as narrow as possible to insure holding tightly. Contact surfaces should be lapped. Passage and sprue holes should be well polished. Many plastic materials contain abrasive constituents and a few like vinylidene chloride and vinyl chloride acetate react chemically with steel (and copper) and make it advisable that dies and heating chamber parts be chrome plated.

Shrinkage allowances must be made to suit both molding temperature difference and time shrinkage recommendations for the particular material. Molding pressure and uniformity of section in the piece and the entry gates are also said to affect shrinkage.

Molding, or preshaping and concurrent or subsequent heating, sintering or baking may be distinguished, though not always too clearly, from the foregoing " casting " methods in which material rendered fluid or semi-fluid before entering, cools or sets in the shape of the receiver. Historically the method dates back to clay bricks and pottery which were molded by hand to bake slowly in the sun, and later more quickly by fire. The low-production foundry technique of molding sand with clay binder (for subsequent casting) is hardly more advanced. Under such titles as compression molding, briquetting, pelleting, preforming, etc., the method is advanced to the machine stage in the production of pills, buttons, grinding wheels, carbide tools, porous metal bushings, welder tips, tiles, plywood and other laminates, crockery, building blocks, insulators, knobs, tires, caps and on endlessly.

Ceramics, compression molded for general and industrial use, may be typified by Westinghouse Prestite. Its composition is given as Flint, Feldspar, China Clay, Ball Clay and water. These are mixed,

filtered, ground and moistened with water to a properly plastic consistency for molding in conventional hydraulic presses and dies. The molded pieces are conveyed through ovens for drying and then baked with accurate temperature control to set and glaze.

Actually each of the clays, chosen from deposits mined in different localities, contains different percentages of about the same six or eight oxides plus chemically combined water, which is the plasticizer. Thus Flint clay contains about 45 per cent SiO_2, 36 per cent Al_2O_3, 3 per cent each of Fe_2O_3 and CaO plus traces of a couple more and about 12 per cent of water in chemical combination. The analysis of Ball Clay is given much the same but with less CaO and about 18 per cent H_2O. Crystalline Feldspars, such as $KAlSi_3O_8$, are aluminosilicates of potassium, sodium, calcium and rarely barium. Although this suggests the chemical complexity of writing formulae for concretes, ceramics and other natural plastics, the technique of handling them was worked out quite well by the ancients.

Soluplastic and thermosetting seems like a proper way to tag the process although some of the same oxides melted into glass definitely add thermoplastic characteristics. The washed and ground clays are soluble in water which makes possible control of consistency for molding. When heated to the setting temperature, which varies over a considerable range up to dull red (dependent upon constituents), the mixed molecules lose their chemically combined water, soften and contract, similar to recrystallization processes in other materials. They cool to a typical stone-like porcelain which is thereafter impervious to moisture. Differences in recrystallization range of the different oxides and in proportions of natural mixtures necessarily complicates the control. These molded mixed oxides take metal inserts or reenforcements well or adhere to enameling steels as protective finishes. They may be machined between drying and baking and ground after baking. They take many color glazes, are relatively brittle and show tensile strengths of about 5000 psi. compared with 48,000 psi. in compression.

An interesting cross between molded ceramics and powder metallurgy is found in certain (*permalloy*) telephone and radio cores. Here, for high magnetic permeability, granules of iron and nickel or molybdenum are prepared and coated with a thin film (0.000,02 in. approx.) of ceramic clay as an insulator of eddy current losses. The coated granules are die pressed to shape at about 100 tons per sq. in. to a density of about 7.75 g. per cc., and annealed, to restore magnetic quality, and incidentally at a temperature which would set the ceramic as a binder.

Abrasive wheels are molded with pressure, temperature and time combinations to suit the particular mixture. The fillers in the mix are

the hard sharp crystal particles as of silicon carbide or aluminum oxide in iron oxide, for grinding purposes, with such binders as rubber, the clays, phenol-formaldehyde or other thermosetting resins. Metal insert hubs or shanks may be molded in place, using hydraulic presses and heated dies for the resins and rubber; or cold pressing followed by drying and baking for the ceramic clays.

Cemented carbides, for cutting edges, drawing, extrusion, heading and cold-forging dies, spot-welding tips and other points of application of severe and abrasive stress, combine such hard filler materials as tungsten carbide, tantalum carbide, and titanium carbide with such binders as cobalt, nickel and copper. Suitably sized and shaped powders are cold compressed in steel dies and hydraulic presses and sintered or baked in reducing atmosphere well up in the recrystallization range of the binder, or hot pressed at similar temperatures in low pressure (1000 psi.) graphite molds with time allowance for recrystallization of the binder. The latter would make for greater density if die materials were available which would stand up properly to both the pressures and temperatures desired. While compressive strengths of the cured mixtures reach 500,000 to nearly 900,000 psi., the tensile strengths are derived from the 3 to 20 per cent of relatively low strength binder so that the carbides are often molded directly into steel holders or rings. Similarly powdered copper and tungsten-carbide tips molded directly on solid copper electrodes combine conductivity and wear.

Metal powders of many types are compression molded, following much the same rules as govern the synthetic resins as discussed in connection with Figs. 376, 377, and Table XXIII*a*. Fundamentally, suitably prepared powders are pressed in dies to suitable density and intimacy of particle contact. Application of heat for the interatomic welding or bonding may be applied either during pressing or more commonly after pressing in the sintering (baking or recrystallizing) furnace. Subsequent sizing or squeezing operations are common for porous bushings, filters, etc., while further hot pressing or cold forging and intermediate annealing operations are required where greater density is wanted.

Powder preparation for size, purity and proportion in compounding of alloys or mixtures with non-metallic components has been worked out for a wide variety of powders by material suppliers. The size of powders, usually gauged by the standard screen mesh through which they will pass, is highly important to proper flowing, filling and relation of voids in initial compacting. The method of preparation also governs whether particles are more or less equiaxed or relatively flat. The metal powders are successfully handled in much smaller average grain

size than the synthetic resin mixtures, perhaps because of the somewhat similar proportion in molecule sizes.

Non-uniformities in the density of compressed powders in thin and difficult cross-sections are traceable to the tendency of particles to arch and lock, leaving local voids, and to pack more tightly close to the striking surfaces, leaving less dense areas farther in, perhaps because of inertia of the particles as well as wall friction. High polish or super-finishing of die wall surfaces is sufficient correction in most cases. Slight reverse tapering of walls, to be corrected if necessary by subsequent ironing or sizing, is also possible. In some cases the die ring is floated on springs to travel down toward the end of the compression stroke to equalize the density. In other cases, both hydraulic and mechanical presses are selected with double actions timed to permit desired relative movement of punches and die walls, or with top and bottom movements to compress simultaneously from the two directions.

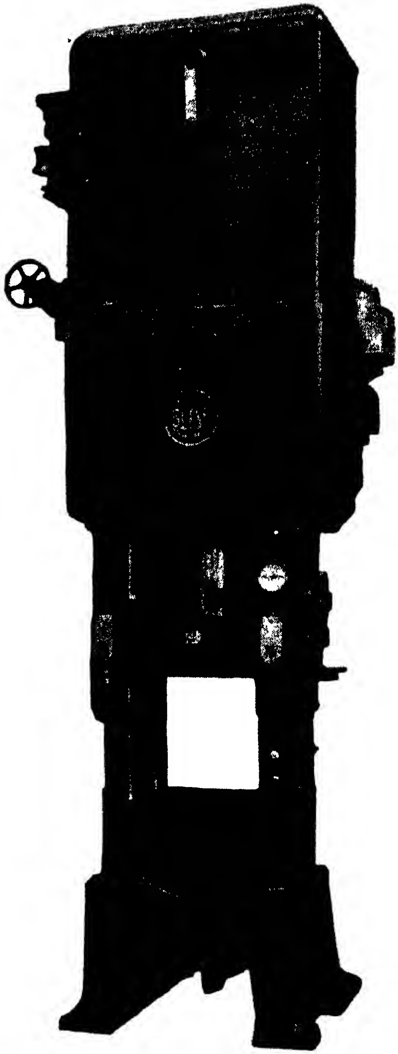


FIG. 391.—A 200-ton fast-cycle Hydro-dynamic molding press with bottom cylinder. Its flexibility in this application favors a variety of metal powder pressing operations.

Fig. 391 illustrates a powder-metal-molding press typical of the fast acting self-contained hydraulic types. This one is being used in compressing copper powders for electrical parts of complicated shape, and assemblies of copper powders and rods, sometimes in place in steel stampings. Oil in the tank at the top is the pressure medium, with variable delivery pump and motor at the rear. Limiting positions of the quick advance, the pressing stroke, the quick return, and the knockout (below) are con-

veniently adjustable. Both pressure and position stops are provided to govern the work stroke.

Porous and *oil impregnated bushings* for self-lubrication are now commonly mass produced in competition with solid bushings. Often iron powder bushings use a small percentage of copper as a binder and are sintered in a hydrogen atmosphere well up in the recrystallization range of copper, so that a copper-iron solution (eutectic) can form at the contact points to join the iron particles as in copper brazing. In the

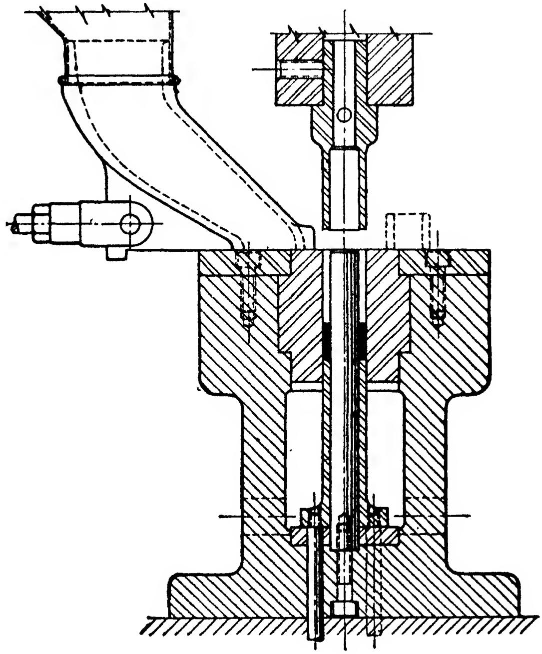


FIG. 392.—Die with highly polished walls for measuring (flush fill) and briquetting porous bronze and iron bushings in mechanical presses, Fig. 394, or hydraulic presses such as Fig. 391.

bronze bearings the tin is activated to form the copper-tin bonding eutectic among the copper grains.

Dies, Fig. 392, for the preliminary molding or briquetting of the powder serve also for metering the charge (for compression ratio in the neighborhood of 3 : 1) requiring careful uniformity in the preparation of powders and lubricants. After sintering, the dies, Fig. 393, for sizing to precise dimension have much in common with other metal sizing or ironing operations described earlier. Both the briquetting and sizing dies are of substantial construction and for production pur-

poses Langhammer and Smith[1] advise high-speed steels for dies and punches and oil-hardening steels for strippers and knockouts. Allowances for sintering contraction and subsequent sizing are suggested as 1 per cent each on the briquetting die diameter. They specify dimensional tolerances of 0.0002 in. and superfinished surfaces. Such accuracy indicates need for solid frame or keyed housing presses which are widely

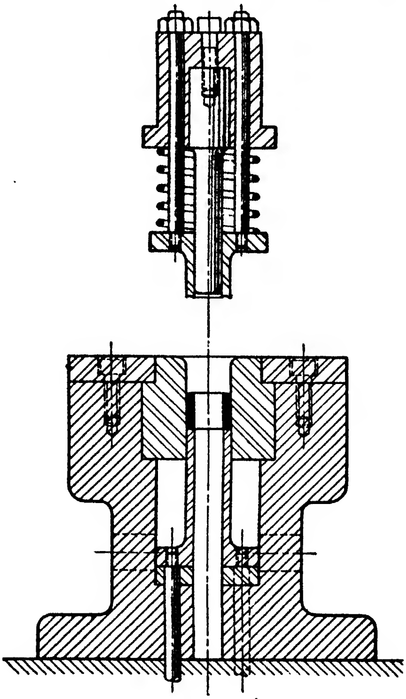


FIG. 393.—Sizing of porous metal bushings after sintering, as performed in either single-action or double-action (Fig. 395) mechanical presses.

used. Mechanical presses, Figs. 394 and 395, usually with cam-actuated, direct or pneumatic bottom knockouts appear preferable for porous metal production work in view of precision, speed and positive bottom stroke position. Hydraulic housing type presses, Figs. 183*a*, 291, give precision plus pressure control for high density compression (20 to 100 tons per sq. in.) for gears and other shaped parts which would otherwise require excessive machining and grinding. Dies for such parts require the rugged construction characteristics of cold-forging dies, with hardened backing or load distributing plates, shrunk rings or

[1] A. J. Langhammer, Milton F. Smith, Amplex Division, Chrysler Corp., in *Powder Metallurgy*, A.S.M., 1942.

wedge prestressing of substantial holders to take spreading strains. Some shapes are such as to require split dies and double-action presses,

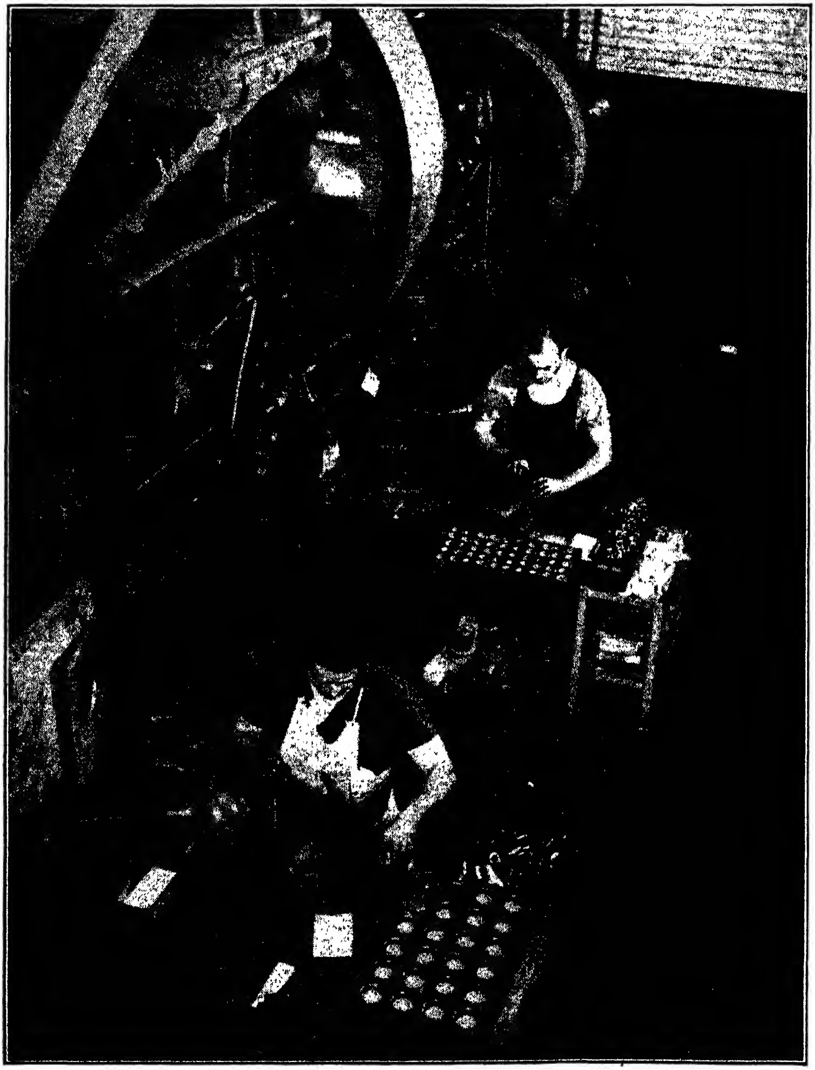


FIG. 394.—Straight-sided and inclinable presses used at the Moraine Products division of the General Motors Corporation in the mass production from powders of bronze and iron bearings. (*Courtesy The Modern Industrial Press.*)

Figs. 291 and 395. The toggle press, in the latter illustration, has the outer slide timed to dwell for holding during the sizing of porous bushings

and also during stripping. Press working pressures bear obvious relation to the yield point of the material being worked. They are usually below the yield point for porous jobs and above, by a small or large amount for high density work, depending upon confinement in the die, restrictions to flow, rigidity and speed considerations, etc.

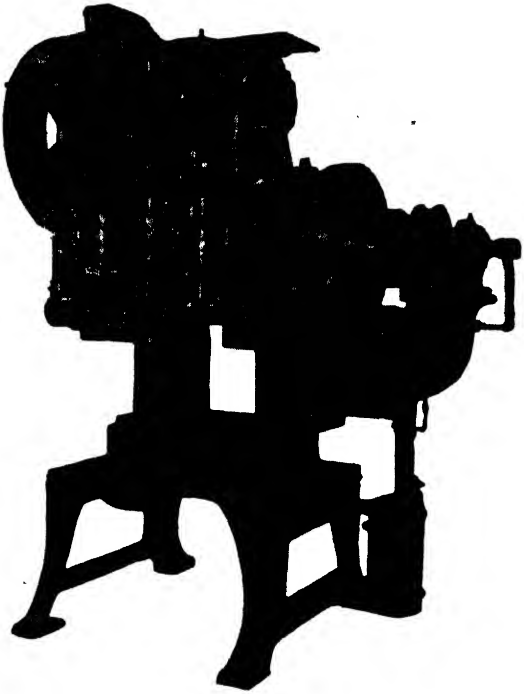


FIG. 395.—Double-action toggle presses, used for sizing of porous metal bushings, offer some advantage in die construction and operation over that in Fig. 393. They also permit closing split molds for other powder briquetting.

Synthetic resins alone in some cases, or with oily plasticizers and organic, ceramic or mineral fillers, as discussed in the preceding chapter, are widely compression molded. This process is of course the predecessor to injection molding, Fig. 390, which has adapted the same general principles to automatic operation with substantial advantage in time cycle, heat transfer efficiency and control. Distinctions between behaviors of thermoplastics and thermosetting mixtures were drawn in Chapter XVI and in discussing injection molding. Most powders if handled with sufficient care, can be measured from hoppers by volume. Mixtures containing macerated bits of cloth for high impact filler and

some other fillers complicate flow sufficiently to require hand weighing of individual charges. In some cases it is economical to use preforms or briquettes compressed to pellet or intermediate shape suitable to the die in small presses or rotary automatic machines. Thermosetting preforms may be preheated on hot plates or (for greater internal uniformity and speed) by high-frequency oscillator, before placing in the

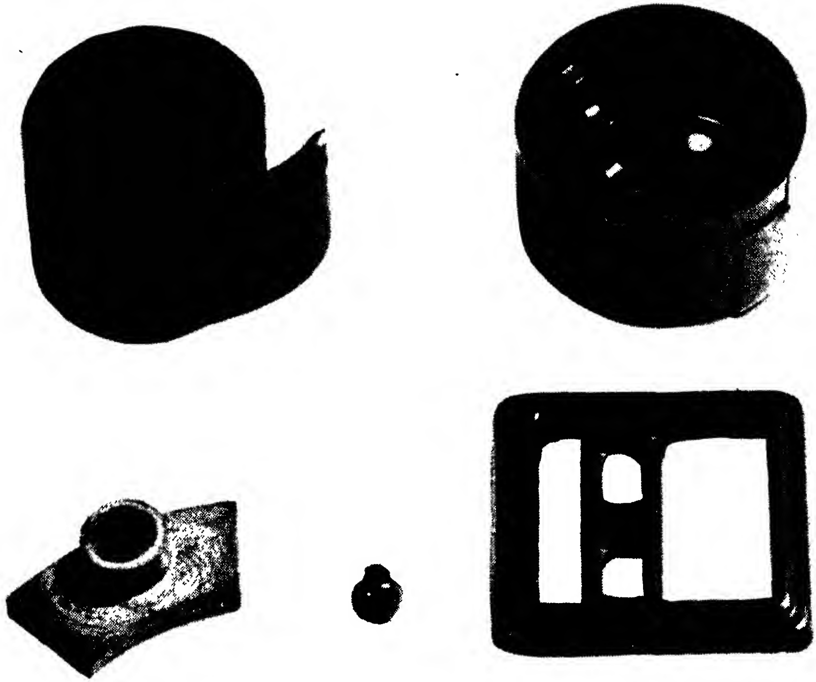


FIG. 396.—Compression-molded thermosetting parts, in this case using impregnated creped paper and fabric coils as preforms. (*Courtesy Cincinnati Industries, Inc.*)

die. For high impact strength, preforms may take the shape of phenolic impregnated paper or fabric as in the case of the parts shown in Fig. 396. These were produced in regular compression molding dies from creped coil stock carrying up to 55 per cent of resin. The mass flowed to fill sharp outlines from preforms wound to suit.

Trapped gasses, as flaw producers, are even more of a problem in working with powders than is the case with casting methods. Proper size and uniformity of granules for mobility leaves considerable intermediate space for air which must be eliminated in compacting the mass. Moisture picked up from the air by wood flour or other thirsty constituents, goes into steam as the heat penetrates. Volatile constituents

of unsuitable plasticizers must also be eliminated. Unless gassing is eliminated or porous mold materials can be used (e.g. sand, plaster, powder-metals); suitable venting must be worked out in die casting or injection molding; or as in compression molding, a "*breathing*" *period* must be allowed by partially reopening the die after the initial

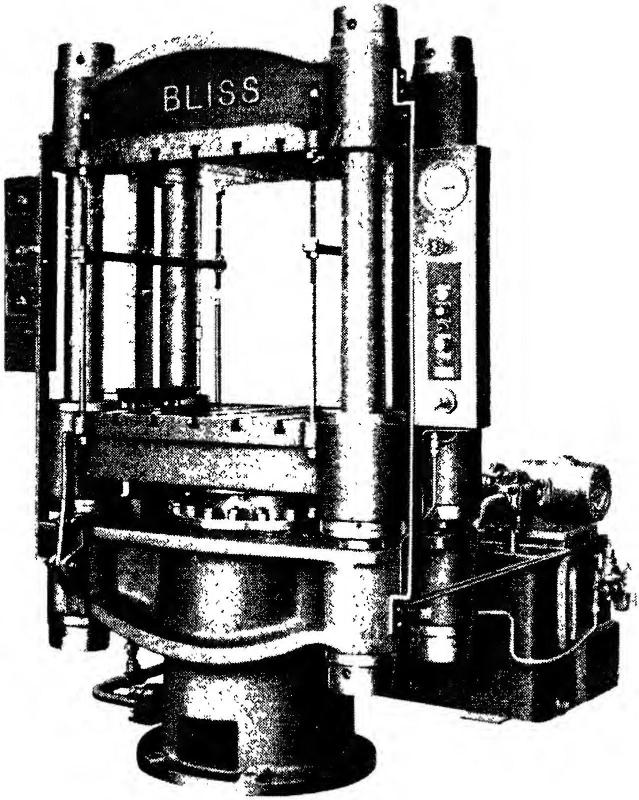


FIG. 397.—Compression molding press, semi-automatic having adjustable preheat, gassing and final cure timers, with individual high-speed pump unit and controls for flexibility in pressure control and operation.

squeeze and warming up. *Preforming* or pelleting eliminates much of the trapped air in some processes. Proper moisture elimination and protection reduces production of steam. Some successful molders find the breathing period unnecessary with suitable material control.

Materials selection and control emphasizes once more the vital role of the chemist in this century's expansion of engineering materials. Development of organic "plastics" like ceramics and even metals,

made initial headway on relatively cheap natural sources such as pine rosins, hide glues, lignin and casein. Complex variety of constitution and impurities made reactions unreliable and difficult to control, contributing to the "finicky" reputation of the process. Industrial by-products which offered cheap sources of chemically more reliable synthetic resin constituents have contributed to more successful general application of plastic molding. Increasing demand makes practical the development of more independent sources of reliable synthetic materials so that the industry may stand on its own feet.

Fig. 397 is a semi-automatic compression molding press. Three electric time adjustments are provided at the left to control successively (*a*) the preliminary cure to presqueeze, heat throughout and vaporize gaseous constituents, (*b*) the gassing period, partially opening the die for escape of gasses, (*c*) the final cure to maintain suitable heat for thorough chemical combination and chain polymerization of thermosetting binders, or for stress relieving to shape and partial cooling of welded thermoplastic powders. For heat economy, thermoplastic filled molds are sometimes transferred from a hot-plate press to a cold-plate press for a final squeeze. The press shown has provision for adjustable top and bottom knockouts, although hand knockouts on the bench and hand control of cycle are used for small lots. The unit shown has its own oil tank, motor and pumping unit for fast, flexible operation and pressure control. Many earlier systems use a central pumping and accumulator unit, usually water account volume and leakage. Two or three supply lines and accumulators at different predetermined pressures combine with return lines and steam lines to link the press groups in what one large operator described as a pipe fitters paradise. Such systems, like line shafting, offered certain initial economies at the probable expense of flexibility and maintenance.

Molds or dies for compression molding are well classified in the Tenite molding handbook[2] as positive, semi-positive and flash types. A positive mold fully confines the material requiring that the charge be weighed with especial care. The more common semi-positive type, Fig. 398, partially confines the material allowing for the overflow of a slightly excessive charge. The flash type mold, like a drop-forging die, confines the material only by reason of the thinness of the flash squeezed out as the two halves close. It is best adapted to large areas, thin

[2] Mold designs vary more with preference than principle, but useful data and examples are to be found in: "Tenite Molding," Tennessee Eastman Corp., Kingsport, Tenn.; "Designing Molded Plastic Parts," General Electric Co., Pittsfield, Mass.; "Plaskon Hand Book," Plaskon Company, Toledo, O.; "Plastics in Engineering," J. Delmonte, 1942, Penton Publishing Co., Cleveland, O.; and other publications.

sections and preforms or blanks prepared from extruded or impregnated sheet materials. A modification of the semi-positive construction

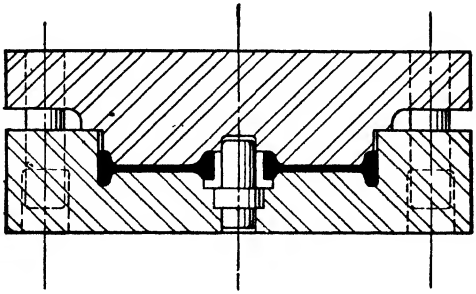


FIG. 398.—Semi-positive compression mold with insert, knockout, slight overflow relief and guide pins.

permits the grouping of several small molds so that they may be filled from a common charge leaving a common flash from which they may be trimmed in an inclinable punch press.

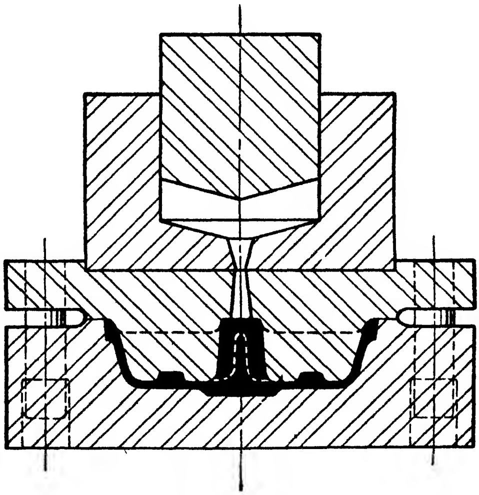


FIG. 399.—A flash mold arranged for use with a transfer molding pot in which the powder charge is plasticized. Note web taper, corner radii and reasonably uniform sections of desirable part design.

Transfer molding, performed in compression molding presses, anticipated injection molding by separating the plasticizing action in a separate chamber above the mold. The four part set up, Fig. 399,

includes a simple cylindrical plunger and pot containing the weighed charge and set on top of and communicating through tapered sprue holes with the two part mold which is usually flash type. The pot and charge may be preheated, and in the case of thermoplastics, may extrude into a cool or cooled mold. The pot and plunger may be used repeatedly with molds requiring more or less similar charges.

Heating or cooling (when it is needed) is usually accomplished, in hand and semi-automatic molding, by running steam under sufficient pressure for the temperature required, or water through drilled plates on the press. A thin film of air retards heat transfer so that surface contacts should be good and joints closely made. Excessive heat or insufficient time for thorough heat penetration result in imperfectly molded parts. If dies are drilled for alternate heating and cooling it should be noted that heat is delivered more quickly from condensing steam than it can be removed by water so that passages should be ample to suit cooling. Shrinkage allowances, venting, knockouts, core inserts and provision for anchoring metal inserts are much the same as for injection molding.

Screen molding, tried experimentally for large area plastic articles, borrows its preparatory technique from paper mill and papier-mâché methods. Here wood pulp is floated in about ten parts of water and distributed over or in a screen or porous mold with the aid of suction for uniformity of distribution. After removal of the bulk of the moisture the shape is separated from the mold with the aid of air pressure and dried. For plastics application the pulp or other organic fiber is mixed with synthetic resin, and the screen process preform is dried and transferred to hot press dies or molds for pressure at curing. Alternative to this is the basically similar method of producing plain or creped resin impregnated papers and fabrics which may be cured to shape as illustrated later.

Sheets, Strips and Strands.—For possibly the most important groups of mass-produced articles, casting and molding are merely intermediate steps in the production of relative thin section sheets, coiled strips, rods and wound strands. These forms of material may be used as such but most go on to varied steps in further fabrication. Methods of fabrication from sheets and strips are of primary interest here, but close inter-relation makes brief consideration of strand production worthwhile.

Tungsten powder, first pressed to close association, then heated in hydrogen well above recrystallization temperatures, then swaged into more compact association, reannealed, reworked now by wire drawing, reannealed, redrawn, etc., finally reaches a fine wire filament with tensile

strengths up to 590,000 psi. Low-carbon steel wire, cast in a billet, rolled hot, rolled cold, annealed, and cold drawn with intermediate anneals achieves a strength almost half as great. Vinylidene chloride powder extruded at temperatures well up in its recrystallization range and subject to stretching and working strain as it cools (Figs. 382 and 383) reaches a tensile strength of 30 to 60,000 psi. Nylon forced through a small die orifice into a solidifying bath and wound under high tension to achieve similar oriented polymer chain results, has exceptional strength (40,000–60,000 psi.) and durability. Glass, representing the ceramics, is drawn from molten form to fine threads and possibly "annealed." These typical strands of widely differing materials proceed to further fabrication by forming, winding, weaving, etc., to take advantage of their distinctive qualities. Somewhat allied extrusion and drawing and draw-bench methods are used in producing rods, tubes and special sections from the various synthetic materials.

Sheet and coil forms of the metals have enjoyed substantial advantage over directly cast or molded forms in certain broad fields of application, and a variety of the non-metallic materials are following along similar lines. The fields are those in which the purpose is served by material which is quite thin in proportion to the area of the part, and in which the non-uniformities of section, characterizing many directly cast or molded parts, either are not necessary or may be rearranged or added to favor the mass-production economies of stamping or forming from sheet. This sheet or coil form has been made economical in turn by development of fast, large volume mills whether for metal, paper, cloth or the formable and curable mixtures.

Steel, mass produced for stamping and forming, suggests the trend for thin plastics. Cast into billets weighing up to 10 tons and more, it may be rolled hot (thermoplastic state) through high-speed progressive mill stands, Fig. 400, then pickled, washed and dried progressively, then cold rolled through fast progressive mills, as in Fig. 4, which are electrically synchronized, then bright annealed in a reducing atmosphere and finally passed through a finishing mill stand for work temper and size. This process is subject to wide variation in practice to suit the output but the millions upon millions invested in mills are responsible for remarkably low price per pound of the metals, and similarly of the papers and fabrics now available.

Paper is the mass-production antecedent of the molded "plastics," and is surging forward as a formable plastic when produced with synthetic resins. Like the molded mixtures it combines a natural polymer fiber filler (usually wood pulp), with an adhesive binder or two, coloring or bleaching matter, and a plasticizer (usually moisture). Breaking

FIG. 400.—This very fast Bliss progressive hot mill and similarly well-developed paper mills point the trend for formable non-metallic thermosetting and thermoplastic materials (synthetic woods, etc.).

up, cleansing and mixing of constituents precedes distribution on screens or screen rolls and subsequent hot rolling with possible intermediate dipping to add coatings, etc. Obviously papers are as varied in composition as the plastics and may include most of the same constituents. Similarly the mills vary from extremely fast high volume newsprint mills to jobbing and specialty mills for quality papers, wall boards, cardboard, uncured thermosetting resin-bearing sheet, cured fibers, etc.

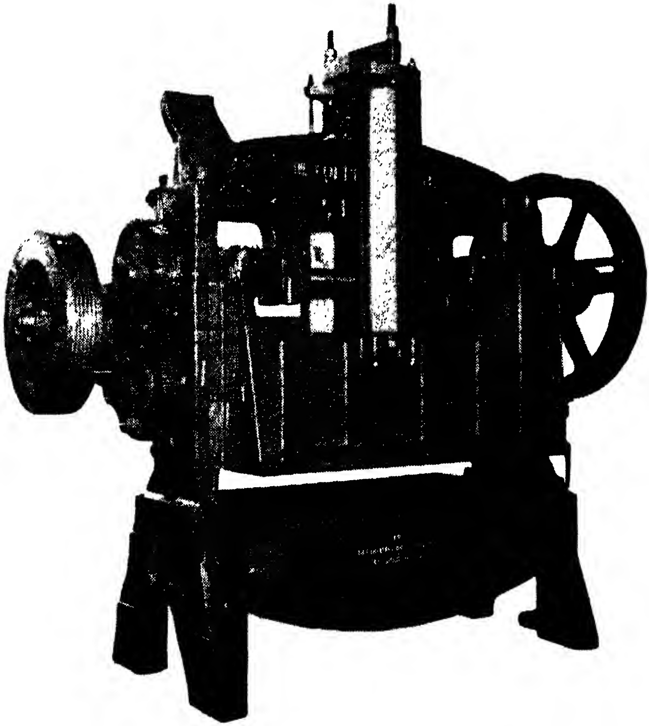


FIG. 401.—Cutting and scoring press for non-metallic sheet materials, in this instance, corrugated cartons.

In the making of cardboard *boxes* and corrugated board *cartons*, the cutting of the outline and the more severe scoring for the folds or bends are performed in a variety of reenforced printing presses and more rugged blanking presses. The carton blanking and scoring press in Fig. 401 has a bed area of 44 in. by 72 in., a rating of about 70 tons and operating speed with automatic feed of about 60 SPM. Structural extension tables, a light reciprocating feed frame driven from the quick return crank at the side of the press, and releasing gripper fingers to carry sheets from the front table to the working position and thence to

the separating and stacking position, complete the unit. The punches, Fig. 402, are built up of steel rule cutting edges and steel or hard brass scoring strips set in a hard wood or masonite matrix screwed to a ¼-in. steel chase or backing plate. Rubber strips tacked or glued to the

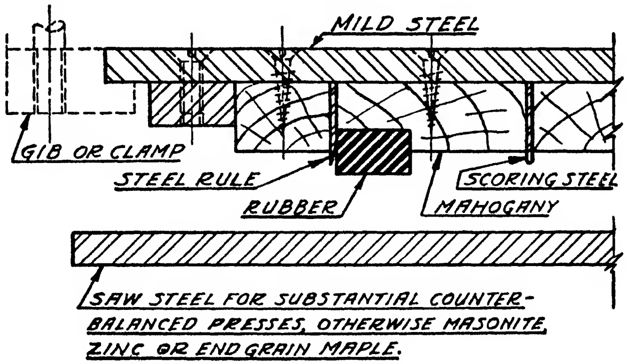


FIG. 402.—Steel rule cutting and scoring dies are inexpensive and easy to slip into place on the press slide.

wood along the cutting edges take care of stripping. This press being rigid and well counterbalanced the knife edges cut against a saw steel plate. Special long slide guides permit offside cutting and scoring as carton sizes vary.

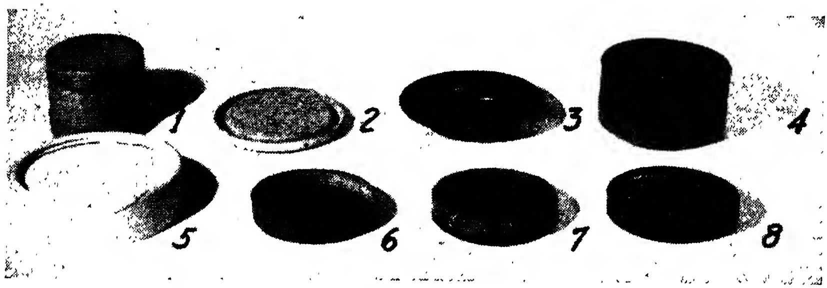


FIG. 403.—Cutting, drawing, curling, folding, ironing, trimming and upsetting operations employed to produce these soluplastic paper base parts. No. 2 also contains thermoplastic paraffin, whereas 3 and 8 contain thermosetting resins, and cure hard and durable.

Paper caps or box covers, spoons, pie plates, round or square picnic dishes, etc., can be drawn, formed and curled quite smoothly though limited in general to fairly shallow shapes, Fig. 403. It was shown in Figs. 135, 136 and 137 that in drawing which involves reduction of circumference, compressive rearrangement of the flange material sets up a tensile strain which increases as the draw becomes deeper or the

reduction becomes greater. Paper is a mixture of various constituents all of which contribute to compressive resistance whereas only the binder contributes to tensile strength. Hence tensile strength of paper is much less than its compressive strength and only a small reduction can be taken at a time. Considering paper as soluplastic and adding water by spray, steam or humid storage to soften it for plastic forming, the moisture must be precisely distributed and just enough added to soften (only) the water soluble binder. Alternative theory indicates

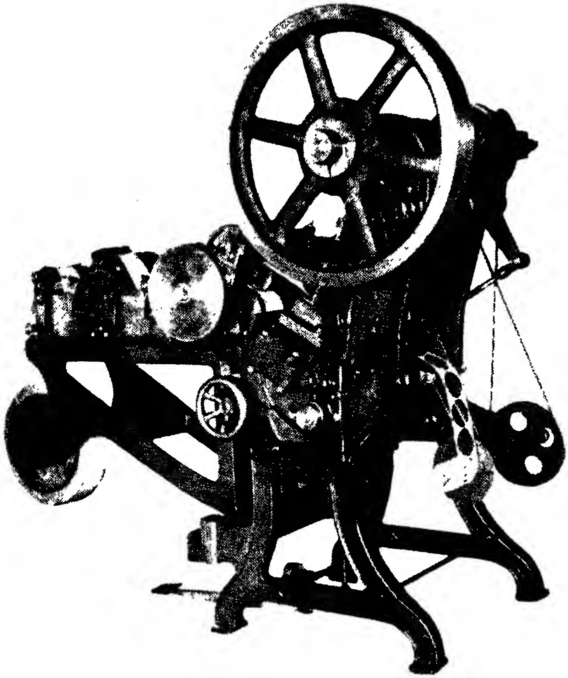


FIG. 404.—A paper cap blanking and drawing press, specially fitted with paper dipping stations.

preference not to remoisten but to retain proper moisture from initial manufacture to fabrication. Whichever is correct, precise moisture regulation has seriously hampered paper forming operations, but electronic control of moisture content, as developed in general paper making, seems to offer a solution. Fig. 387 shows the difference in moisture relation for a few different paper mixtures, and Fig. 388 shows in part the affect of moisture content on physical properties of paper.

Simple cups, see parts 1 and 6, Fig. 403, are blanked and drawn in such combination dies as Figs. 74 and 276, usually heated with steam

or electric heating elements to dry out the plasticizing moisture. Often the cups were pushed down through the die and on through a slightly heated tube to hold the shape a little longer. The presses most often used have been the double-action cam presses, Fig. 277, frequently fitted with roll feeds Fig. 159, although the scrap cutter shown there is likely to be replaced with a rewinder. Fig. 404 shows a Bliss paper cap cam drawing press dating back to 1905 and fitted to dip the paper

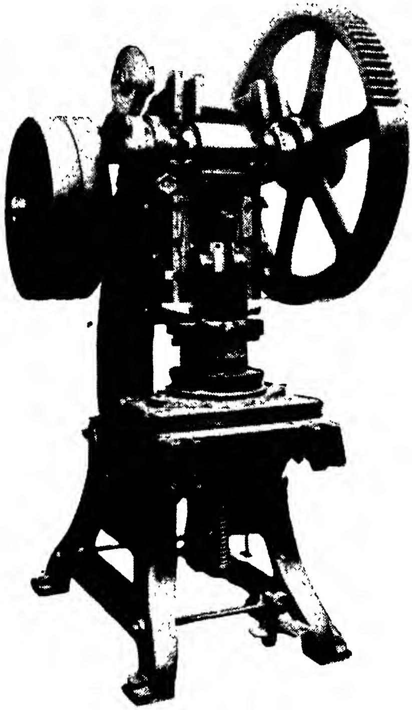


Fig. 405.—A No. 20 inclinable single-action cam press with heated die for a brief dwell (1½ sec.) in molding and setting a plate to shape.

in the course of roll feeding and rewinding it. Operating speeds range around 80 to 140 per minute. Part 4, Fig. 403 was too deep to draw smoothly in one operation without tearing. Accordingly the draw radius was corrugated to fold the surplus material in a series of uniform corrugations and these were ironed together evenly as the shell pushed down through the hot die.

Combinations of roll feeds for coil stock and ratchet or friction dial feeds for secondary operations in completing the part, may be arranged on suitable presses as discussed under automatic feeding in connection-

with Figs. 354 and 355. Thus the hard and durable plastic screw cap, part 8, Fig. 403, was carried through its series of operations in a roll- and dial-fed single-action press. The $\frac{1}{16}$-in. soluplastic and thermosetting (phenolic) paper must be blanked from the coil, hot drawn and crown stamped, upset with a sectional punch and possibly pinch trimmed before it is cured (polymerization is completed).

With proper moisture control and timing some paper shapes can be blanked and formed in fast crank presses (as in powder preforming). Others require a dwell to hold them briefly under pressure for a drying set and frequently with the application of heat. Thus a variety of paper plates, round or rectangular and plain or fluted are cut and formed with the 180° dwell of such a press as that in Fig. 405 at speeds of 20 to 80 SPM. Thermosetting papers may be cured thereafter or preheated and cured quickly in thin sections. Part 7 in Fig. 403 is a soluplastic paper (said to be corn fiber) in which a thermosetting binder (also a corn product) is mixed in the beater in the initial production.

Curling, or false wiring, Fig. 403, part 5, of paper and similar plastic non-metallic materials, acts much like metal curling, Fig. 110 and 114, except that rolls are ordinarily not used. For example, in curling exposed ends of spiral wound tubing, a high-speed head is revolved in proper direction relative to the spiral. Inserted in it instead of curling rolls, are hardened pins, replaceable because of the considerable abrasive action of some constituents of the paper. These pin inserts are grooved to the profile of the desired curl and radiused on the leading or working edge. The use of pins instead of rolls is presumably to generate heat to set the shape.

Thermosetting papers, cured in laminated flat panels or formed and set to shape, Fig. 415, with proper heat and pressure have taken considerable strides in a variety of fields. They naturally offer the same strength, hardness and appearance as molded phenolic, urea and melamine resins made with wood-flour fillers, or possibly even better owing to longer fibers, better arranged in the paper-making process and the need for less plasticizer or lubricant. Obviously thinner sections, in proportion to area, and faster curing times (and therefore less material and manufacturing cost) are possible as compared with more complex parts molded from powders.

Manufacture of resin-bearing papers initially required starting with Kraft or other suitable commercial paper and applying by spray or dip a desired proportion of synthetic resin dissolved in alcohol or other solvent. Some further advantage was gained by large users who recover the solvent from drying towers. To meet demand paper manufacturers are beginning to offer stock in which thermosetting resins have been

combined with wood pulp or other natural fibers in the mixing vats. Expense varies with color, the proportion of resin required and the plasticizer. Water content has been ample plasticizer for handling and forming prior to curing, but it goes off in steam at the cure and may have to be restored or a high-boiling-point plasticizer added to avoid brittleness and jagged fractures in punching.

Thermosetting fabrics impregnated with phenol-formaldehyde and other resins, find substantial demand including panels, gears, bearings, pulleys, tubes, and machined, formed and punched shapes. Fabric as a reenforcement contributes especially to impact strength. Full width coils, narrow slit coils, sheets and macerated filler in fine and coarse weaves are widely used. The cellulose molecule chains of cotton fibers seem especially desirable, but asbestos (crystalline fiber) fabrics for somewhat higher temperature applications, sisal (hemp) fabrics and glass fabrics are also used.

Fig. 406.—A laminated jug cap blanked, drawn and cured from layers of 45% phenolic X-crepe (gathered fabric) at the left. (*Courtesy Cincinnati Industries, Inc.*)

Crepeing or gathering of both paper base and fabric base materials adds greatly to their stretchability or formability without fracturing the reenforcing base material. The samples in Figs. 396 and 406 are interesting in this respect. All are produced from paper and fabric base materials carrying 10 to 50 per cent of resin as required and known as X-crepe. The processed coil stock has crepe puckers or corrugations crossing each other at say 45° each way to the length, giving a 20 or 25 per cent surplus for forming either in single thicknesses or laminated.

Resin bonded fibers promise the manufacturing shortcut of a direct combination of cotton or other vegetable fibers with synthetic resins and plasticizers into an economical formable and/or curable coil material. Reference to the discussion of high-strength synthetic oriented polymer chains in connection with Fig. 382, indicates that naturally

polymerized molecular chain fibers of wood, cotton, hemp, corn, etc., (and in some cases cow hair and wool) may be made the base of high-strength materials. Such fibrous strands, laid parallel and overlapping and impregnated with thermoplastic or thermosetting binders and such plasticizer as may be required, offer a wide range of utility. A combination of initial cotton fabric or felt-making procedure and modified paper-making methods as a basis of economical manufacture has been discussed briefly by Goldman and Olsen.[3]

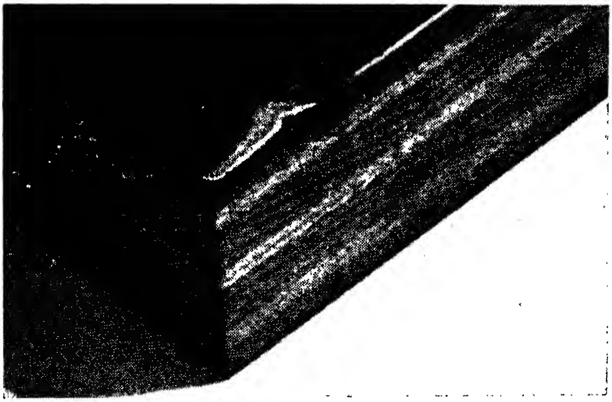


FIG. 407.—Laminated wood cured with decorative color plastic surface, fire-retarding metallic interlayer and impregnated paper backing. (*Courtesy The Formica Insulation Co.*)

Plywood construction is closely related to the foregoing thermosetting papers and fabrics. Tissue-thin paper, impregnated with thermosetting resin or less desirable natural glues, is placed between thin layers of wood with direction of grain crossed diagonally for strength. As many thicknesses of alternate wood and resin as may be required are built up, clamped flat or to shape under sufficient pressure to assure intimate contact, and heat is applied for sufficient time to penetrate and set the resin.

The "low-pressure method" applied to emergency forming of airplane and boat sections involves fitting, tacking and clamping the alternate plys of wood and resin tissue sheets to shape in or over a form, clamping a rubber blanket or cover tightly over exposed surfaces, exhausting air under the blanket and inserting the whole assembly in a high-pressure steam chamber or auto-clave. The steam pressure of 75 to 300 psi. and such local clamping pressures as are possible, are then

[3] *Modern Plastics*, May, 1943, p. 100.

responsible for *continuity of contact to* assure good joining of the plys. Temperatures of 275 to 350° F. are maintained throughout the chamber for periods of 15 to 30 minutes or more, for wood, like the plastics, is a poor heat conductor and the heat must penetrate for the resin layers to adhere properly.

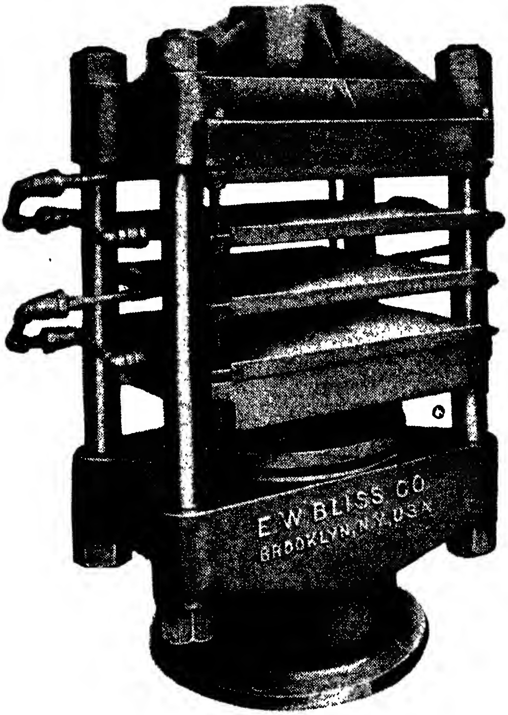


FIG. 408.—Hydraulic presses for laminated sheet curing have been characterized by many steam platens to compensate for poor conductivity and therefore long-curing cycles.

In general, however, it is preferred to apply positive pressures of 1000 to 3000 psi. to assure proper contact during curing and, for greater strength, to compress the normally porous structure of the wood. Plywood may be combined in curing with a variety of other sheet materials for decoration or utility. Thus it may have a surface layer of impregnated paper in color, or of fabric or even metal foil for reenforcement, or of impregnated grain wood veneer as for durable hotel bureau tops. In such cases, however, a balancing layer must be cured on the reverse side to avoid distorting strains and keep the finished sheet flat. Fig. 407 illustrates a table top section built up in such a way.

Flat laminated sheets of thermosetting resins in paper, cloth or plywood have long been cured by piling lamination layers to proper thickness with supporting and separating steel plates where necessary, and placing between steam-heating platens in such a press as that shown in Fig. 408. Pressures recommended are 1000 to 3000 psi. and tempera-

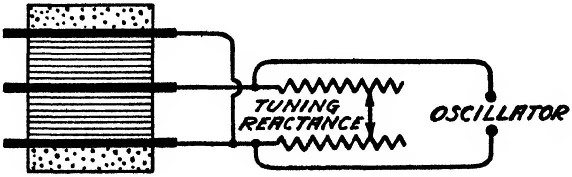


Fig. 409.—Balanced hook-up for high-frequency dielectric heating in which outer plates of similar polarity may be insulated from or grounded on press surfaces.

tures of 275 to 350° F. for sufficient time to permit the heat to penetrate throughout the stack to assure a uniform cure. Heating times of several minutes to an hour or more, dependent upon thickness, have been common with contact heating as by steam plates. Alternatively, high-frequency dielectric heating,[4] Figs. 409, 410, operates upon the molec-

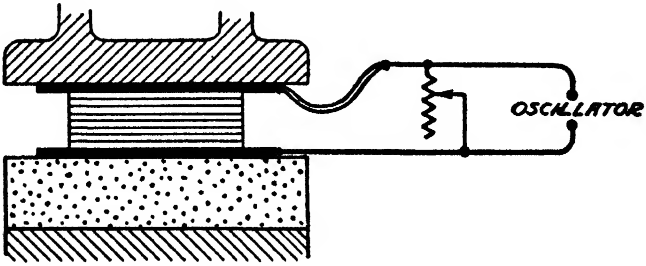


Fig. 410.—Dielectric heating arrangement in which one plate must be amply insulated from press frame. Tuning adjustment required to suit thickness and resistance of material to be heated.

ular structure throughout the mass simultaneously and reduces these heating times to a small fraction of that required by conduction. The high-frequency oscillator unit not shown in the diagram is complex electrically, but the expense involved seems likely to be substantially reduced.

Piercing, blanking and shearing of laminated materials is subject to certain limitations. Where a number of layers of material, whether

[4] "Heating Wood with Radio Frequency Power," John P. Taylor, R.C.A. Mfg. Co., presented before A.S.M.E. Oct. 12, 1942.

metal, paper, laminated plastic or whatever, are cut between the edges of a male punch entering a well-ground die, the top and bottom layers, which are in close contact with the cutting edges, will cut cleanly, but these surface layers tend to mask the sharpness of the edge, and intermediate layers tend to pinch off or tear. In relatively thin laminated materials this tendency is negligible, but in thick stacks it may produce

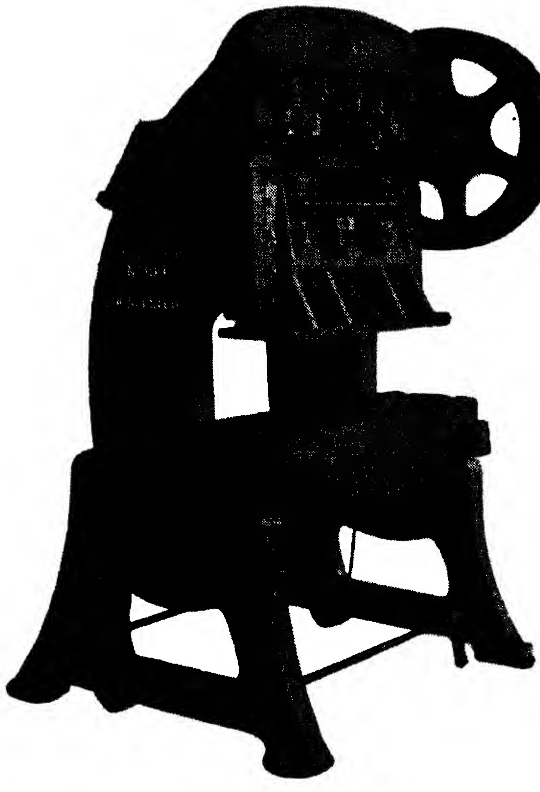


Fig. 411.—Inclinable presses, both single- and double-crank types prove most convenient for feeding in cutting blanks and trimming of plastics, fabrics, laminates, plastic impregnated felt (gaskets), etc.

a rather ragged appearing fracture. Shaving cuts with a sharp edge having a 45° back angle are said to be satisfactory if not more than 1/16 in. is removed per cut. The softer or spongier the material, the greater is edge distortion likely to be. Accordingly, in cutting thick stacks of paper, cardboard, cloth and some of the laminated plastics, it is common to use *knife-edge type dies*, known as dinking dies, hollow cutters and steel-rule dies (Fig. 402). Although such cutting is usually

slower than male and female die work, the knife edge is driven through, cutting all layers cleanly down to a bottom plate which may be saw steel, zinc, masonite, end-grain maple, etc. The hollow cutters are often moved about over the material to be cut, and located by hand in

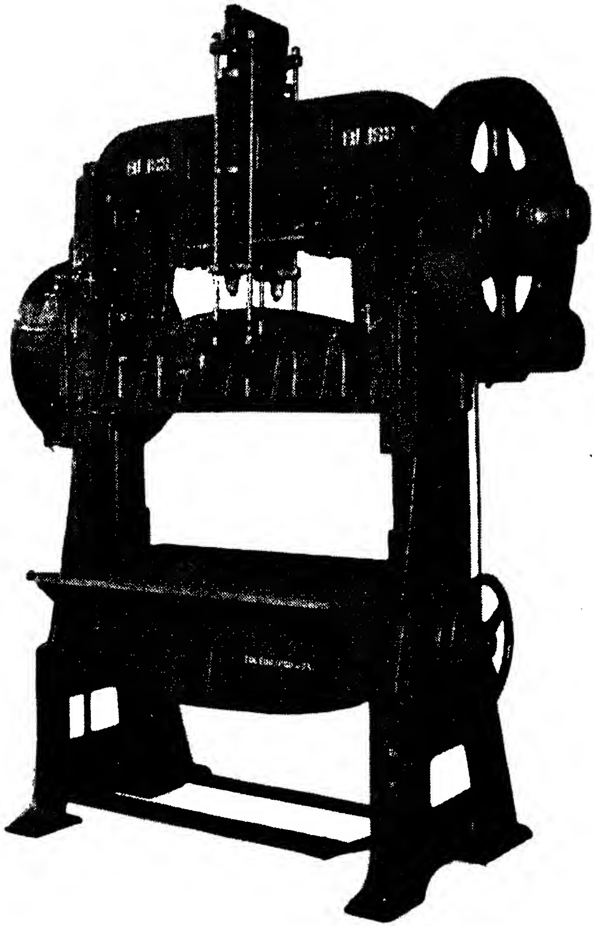


FIG. 412.—For hollow cutter blanking of multiple thicknesses, this press is fitted with bottom adjustment to permit refinishing a wood cutting block.

gap frame inclinable double-crank presses, Fig. 411. In another type, Fig. 412, a considerable bottom adjustment is provided to compensate as 10 in. high end-grain maple die blocks are gradually planed down. As used in the cotton glove trade, long piles of fabric about 6 in. high (squeezing to about 2 in. under cutting pressure) are moved by hand-wheel conveyor through the press. The Mehle hollow cutters, follow-

ing the profiles of the glove pattern, are moved back and forth under the slide, locating by eye for maximum economy of material. Note on page 80 that knife-edge cutting loads are given in pounds per inch for a particular material and are practically independent of material thickness. For smooth edge blanking of laminated materials in production, Fig. 413 offers a means of rigidly mounting the hollow cutter, inverted for push-through operation and provided with a male punch for clean cutting, and with spring strippers.

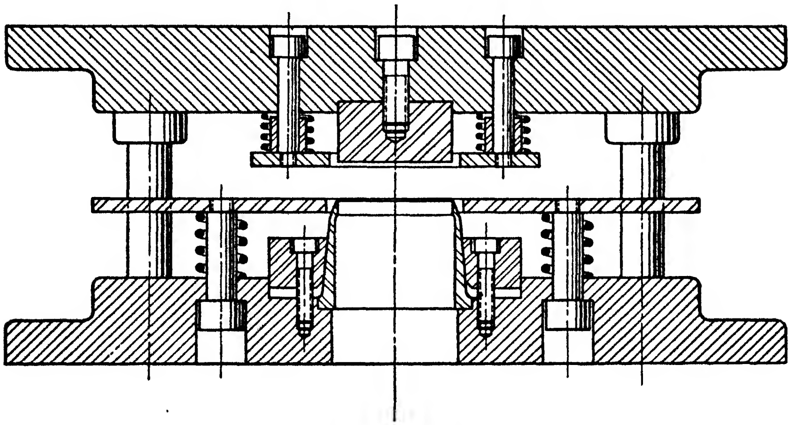


FIG. 413.—For smooth-edge production blanking of laminated materials, a hollow cutter is rigidly mounted in inverted position.

Cured phenolic laminated sheets and strips for punching require suitable plasticizers included in their preparation to avoid brittle cracking and to adapt them to the many piercing and blanking operations in producing thin insulator pieces, covers, separators, gaskets, etc. Most thin paper, fabric, and asbestos fabric base phenolics (up to $\frac{1}{16}$ in. or $\frac{1}{8}$ in.) may be punched at normal room temperatures, though in many cases and for thicker sheets (up to $\frac{1}{4}$ in.) the results for both punching and slitting are better if warmed up. The Westinghouse Micarta Data Book gives a number of excellent rules, interpreted as follows:

Minimum space between pierced holes = $3 \times t$ (thickness).
Minimum scrap margin allowance = $3 \times t$. Clearance between punch and die $0.05t$ all around, or $0.10t$ on the diameter.
Where close sizes are required, allow something for elastic contraction of holes or expansion of blanks when cold punched.
In hot punching allow also for contraction in cooling.
For hot punching 212 to 250° F. is recommended.

Material should be well spaced in the oven and heated only long enough for uniform penetration (approx. 5 min. for $\frac{1}{16}$ in. t to 30 min. for $\frac{1}{4}$ in. t).

For both punching and shearing the cutting edges must be kept sharp. Thicknesses in square-shearing are limited to $\frac{1}{32}$ in. to $\frac{1}{16}$ in. cold and up to about $\frac{1}{8}$ in. hot.

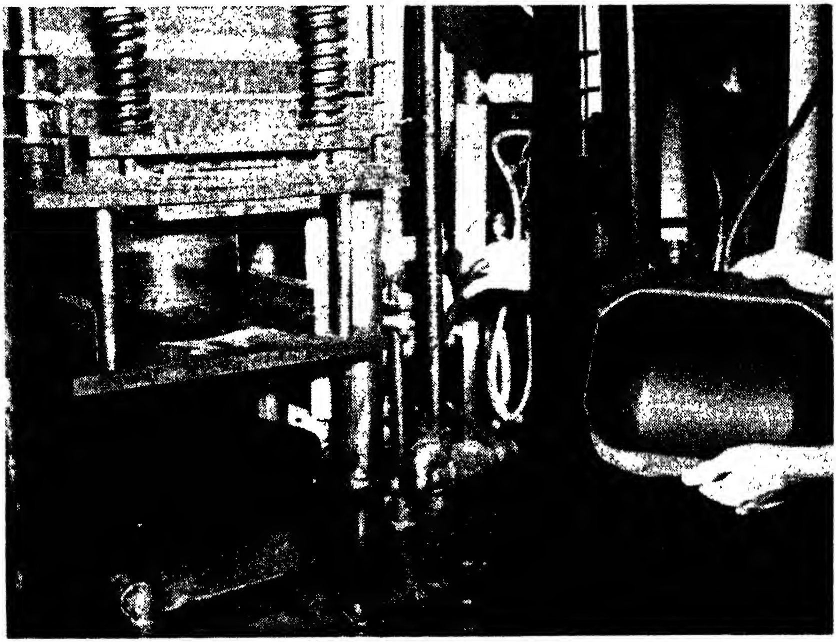


FIG. 414.—Blanks of proper shape and correct moisture content, drawn in a double-action die and cured under pressure, produce tough masks and helmets. (*Courtesy Continental Diamond Fibre Co.*)

Uncured impregnated papers and fabrics are easily pierced and blanked from coil or sheet stock in either male and female dies or hollow cutters. Papers permit forming to shapes, including shallow draws and some stretching before curing, Figs. 403 and 415. Creped stocks add greatly to the drawing range, including almost complete hemispheres. Loose-woven and creped fabrics permit very considerable forming and flowing in the curing dies. Developed, notched, blanks cut out of phenolic impregnated canvas as in the case of army helmets and safety hats, may be combined with extra strips or inserts, and overlapped or butted at the joints and the assembly welds into a smooth mass in the curing die, compressing or spreading to give a uniform fill or to take

care of change of section. Other assemblies may be built up for wear or impact strength with canvas side members, macerated, flour or coil fillers possibly premolded with little or no heat to hold together, then fitted with inserts and finished cured to final shape and size. Some of the creped materials in small coils may also serve as preforms to flow into thin or odd sectioned moldings where impact strength is needed, Fig. 396. Referring again to plastic safety helmets, an interesting design, Fig. 414 is deep drawn, probably with some stretching, in a

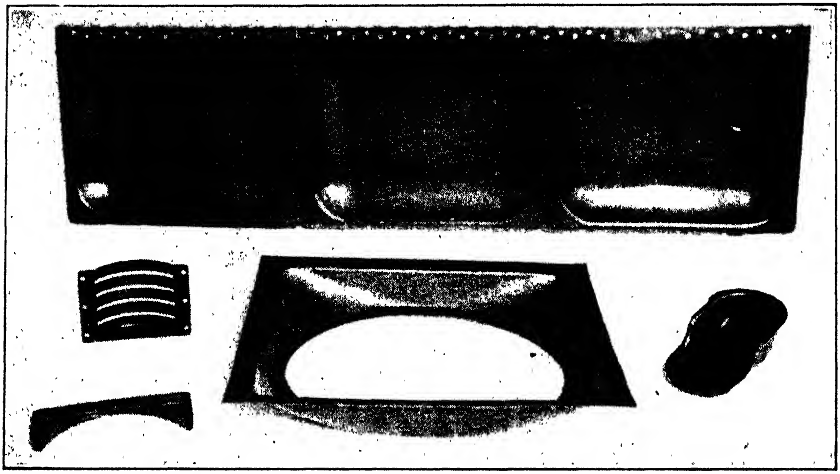


FIG. 415.—Substitution for aluminum stampings of pressure cured phenolic paper "stampings" having 8000 p.s.i. tensile and 40,000 p.s.i. compressive strengths. The group of three have plywood inserts and were made on low cost temporary dies. (*Courtesy Brunswicke-Balke-Collender Co.*)

regular double-action draw die. The material is a moistened soluplastic cotton rag fiber. The press is a single-action hydraulic with spring-drawing attachment.

Tough and resilient airplane wing tips and large interior sections, refrigerator door liners, etc., illustrate the trend to large-area thin-section shapes with or without integrally cured reenforcements as made by the impregnated sheet process. The larger drawn phenolic-and-paper laminated parts in Fig. 415 are cured with plywood inserts in place. For the thin sections involved steam-heated dies are fairly fast but dielectric heating is promising for production purposes. Inflexible central system hydraulic presses have initiated the work, but faster self-contained hydraulic presses, Figs. 291 and 416, and several available designs of mechanical bottom stop curing presses, such as those in

Figs. 417 and 419, offer substantial production advantage. These presses may be had in both single- and double-action types of almost any bed area. With uniform sections of impregnated sheet materials, working pressures may go as low as 100 to 250 psi., and as non-uniformi-

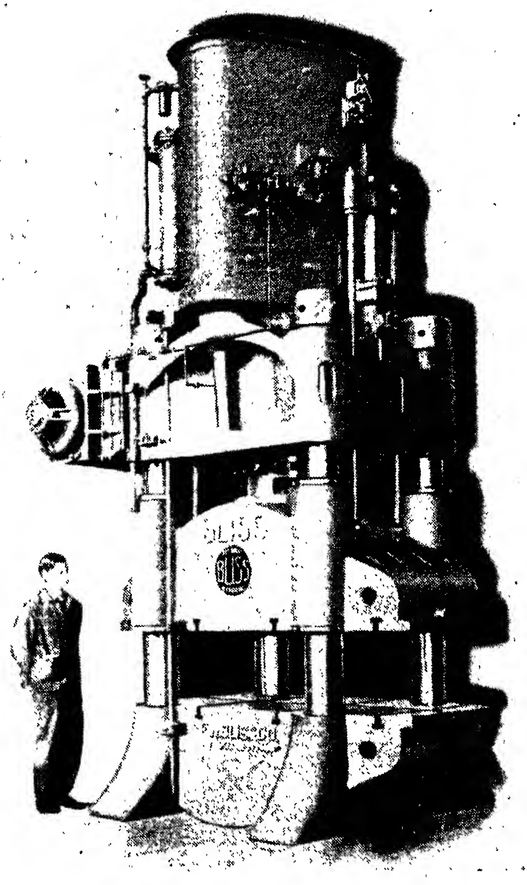


FIG. 416.—A flexible, independent unit with variable delivery pump, quick advance, precisely controllable pressure cycle and quick return.

ties of section develop, may rise to 1000 to 3000 psi. Curing temperatures vary with the resins in the neighborhood of 240 to 400° F. or higher for some of the new materials. Trimming and piercing of cured shapes follows the rules for similar thermosetting flat laminates.

Thermoplastic resins in sheet and coil form include transparent and opaque flats, thermoplastic woven fabrics and other fabrics and papers

impregnated with thermoplastic resins. It is interesting that some thermoplastic "waterproofed" fabrics have been sewn together by what might be described as dielectric seam welding and thermoplastic tubing has been butt-welded by hot-plate heating of the ends, suggesting also thermoplastic spot or shot-welding probabilities. Most of the thermo-

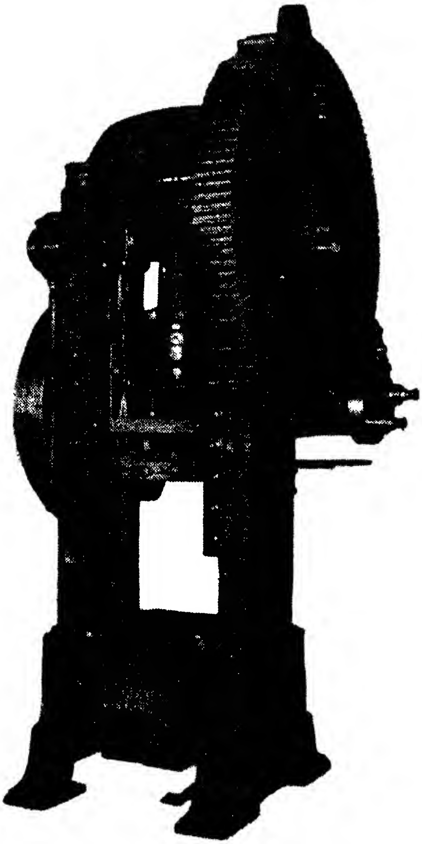


FIG. 417.—This fast compression molding press, used for thin sheet plastics, gives timed bottom-stop curing, available also in double-crank and double-action types.

plastic resins are also soluplastic and may be softened and shaped or stuck together by the use of suitable solvents.

Thermoplastic resins behave very much like metals in their thermoplastic or hot-forging range. The resins, however, contain say 7 to 50 per cent of suitable plasticizers for flexibility or avoidance of brittleness. Such plasticizers contribute little or nothing to tensile strength so that

drawing is again limited to materially less than the 50 per cent reduction which is the limit for materials having equal yield points in compression and tension (Figs. 136, 138 and page 158).

Temperature and time relations are important to the success of most operations. Fast high-frequency dielectric heating heats simultaneously throughout the material or the portion of the material between condensor plates. Other methods, limited in temperature to avoid excessive heating, require time for penetration of heat, increasing with thickness, as most resinous thermoplastics are slow heat conductors.

FIG. 418.—Thermoplastic cellulose acetate is hot drawn and stress relieved before releasing, to hold the shape. (See also Figs. 403 and 404.) (*Courtesy Celanese Celluloid Corporation.*)

The relation between temperature, plasticity and relative elastic spring-back are indicated in Figs. 373, 374 and the data given with them. Temperature must be high enough to permit change of shape without fracture of the particular material or mixture. If it is not high enough for immediate or spontaneous stress relief then the shape must be held long enough above the recrystallization temperature, Fig. 376, to permit easing of intermolecular strains to avoid spring-back. If temperature is so high that gravity strains might distort the formed piece, then the shape must be held until cooled enough to retain its profiles.

Fig. 418 shows three shapes drawn from cellulose acetate (Lumarith) sheet. The reverse drawn small part was pinch trimmed from an over-size blank and the flange resistance in drawing was such that consider-

able stretching took place, reducing the material thickness about 50 per cent in the inner sections. The other two were double-action draw jobs following the principles of Fig. 135. Both were drawn over rather small draw radii and pinch-trimmed (see Fig. 62) by a shoulder on the draw punch. The deeper cup figures about 37 per cent reduction. Presumably for relatively deeper shells, these might be redrawn in a series of easy reductions, either at one heat or with intermediate rewarming. Localized preheating of the areas subject to plastic rearrangement

Fig. 419.—A No. 19 Bliss compression molding toggle press, regularly fitted with adjustable electronic timing of bottom dwell period, for mica parts, cellulose-nitrate formed numbers, etc.

is likely to be advantageous in some cases and it is probable that electronic heating of the area in contact with an insulated blankholding ring may prove advantageous in production. Light gauge rectangular shapes as for radio dial windows and large ⅛-in thick rectangular dishes with a pouring spout at one corner are examples of odd shapes drawn in cellulose thermoplastics. Cellulose nitrate numbers are drawn in presses like that in Fig. 419, having a timed bottom stroke dwell to allow completion of stress relief in order to hold shape. Along similar

lines are bottom stop and bottom dwell presses in Figs. 250 and 405 for rubber, mica with plastic binder, papers, celluloid and other cellulose mixtures. Successful bottom stop mechanical presses require that the slide or ram drive decelerate smoothly to a precise stop on bottom center and accelerate with proper mechanical advantage at the completion of the time period. Adjustable electronic timers are available for both mechanical and hydraulic presses.

Optical clarity and smoothness are essential after forming of some transparent thermoplastics such as methyl methacrylates and cellulose acetates for aircraft contour windows. Differences between the plastic ranges and working temperatures of these two thermoplastics were noted in Figs. 373 and 374. Punches may be made of plaster, plastics, zinc or other smooth-finish material but even so should be covered smoothly with thin felt, canton flannel or stretchable rubber-backed suede, and should be protected from dust which is likely to cause light-distorting imperfections. In all such shallow profile forming the material must be firmly gripped and stretched to the shape and then held to stress relieve and to cool sufficiently for handling.

Curling operations may be performed with a revolving head as in paper and metal working. Letter stamping and marking operations with brass or steel dies are performed with a comparatively brief dwell for setting or stress relief. Where markings must remain accurate and should therefore be impressed at normal room temperatures, it is necessary to select a material which is still thermoplastic at or below room temperature.

Brittleness, causing splitting, crazing or fractures from a sheared edge, is especially likely below the thermoplastic range of materials which are not plastic in the crystalline state. See also Fig. 108 and page 117. The sharp break at the end of the elastic curves at the lower temperatures indicates such brittleness in Figs. 373 and 374. Synthetic plastics having thermoplastic ranges beginning below normal room temperature include in general cellulose nitrate, cellulose acetates, ethyl cellulose, vinylidene chloride, etc., which may therefore be punched and sheared without heating. Methyl methacrylate, other acrylics and styrenes, however, have higher ranges and are likely to require warming up. The higher the temperature, however, the greater is the tendency to drag down to a rounded edge and to close in the hole size in punching.

Blanking, piercing, trimming and other operations discussed in Chapter IV are practical for organic thermoplastics in much the same way as for metals. Shaving operations may also be used. The light cutting loads permit the use of knife-edged hollow cutters and steel-rule

dies in single or multiple thicknesses as in the case of paper and cardboard.

Bending operations are difficult only in that the greater elasticity of the material requires either a considerable overbend or suitable temperature and time for stress relief, Fig. 376, to hold the bend.

Bonded metal-" plastic " and other combinations of bonded materials continue to offer a more or less unlimited field. The bonding of metal to metal by plating, spraying and roll-welding is commonplace. The pressure-welding of powdered metals to metals is becoming familiar, Fig. 391, as in the production of copper electrodes durably tipped with sintered copper and tungsten, or copper and tungsten carbide; and of steel dies and cutting tools faced or edged with tantalum or other carbides and cobalt or other binder. Copper and silver brazing of steel parts enter into the same scheme of joining by surface alloying or welding. In general a molecular attraction or chemical affinity is fostered under pressure (for intimate contact) at temperatures above the recrystallization range of one or both constituents (for molecular readjustment).

Metals coated on one side with protective lacquer and on the other with decorative thermoplastic paints are deep-drawn, threaded (by rolling), knurled, curled and otherwise severely worked with little or no damage to the coatings as in the manufacture of screw caps decorated cans, toys, etc. Metals have long been sprayed with ceramic clays and color pigments and baked to a hard porcelain finish for tubs, kitchen ware, etc. The bonding of organic or synthetic rubber to metal for highly stressed shock-absorbing mountings, seals, bumpers, treads, etc., is well known. Combination of plasters, insulating materials, reenforcing or fire retarding metals, metal inserts and durable, decorative synthetic surfaces in economically produced sheets is gaining impetus. Fig. 407 showed a fire-retarding composite section of plywood, thin metal and colored non-inflammable synthetic surface used for table tops, doors, etc.

Properties of the infinite number of alloys, synthetic or natural combinations or mixtures of the chemical elements can only be given in barest outline in the plastic properties tables in the Appendix. Most metal manufacturers are publishing constituents, approximate proportions and some physical and chemical properties of the materials they offer. Non-metallic material producers have done a pretty good job with presentation of chemical, electrical and some physical properties but the wide range (minimum to maximum) of these properties and the lack of listing of constituents and proportions suggests some uncertainty, particularly in the matter of possibly unstable plasticizers. No hand-

book or other compendium has yet undertaken the definitely unstable task of listing the wide range of engineering materials and their wanted properties.

Methods of plastically working metallic and non-metallic materials have been illustrated in a variety of ways. Temperature and time requirements have been shown to vary with the type or types of plasticity characteristic of the material or mixture. The tools, be they called dies, molds or whatever, to produce a particular shape depend upon pressure intensity, proportions and production requirements. Metal working, in the earlier chapters, has been discussed at greater length because of its earlier adaptation to mass production methods. Note, however, that regardless of whether the material is metallic, organic, ceramic or a mixture of these, the same basic principles govern plastic flow in the several states of plasticity.

APPENDIX I

GRAPHICAL COMPUTATIONS

ALIGNMENT diagrams may frequently be used to advantage in making quick approximations which are sufficiently close for engineering purposes. *Such diagrams must be used with judgment and with frequent allowances for intangibles.*

The charts which follow are grouped to include, first, the computation of the pressure and work requirements of the particular metal-working job, and second, the pressure and work capacities of the press which is to do it. Most of the formulae used are selected from those which have been developed and explained at length in foregoing chapters. In arranging the charts suitable constants have been included so that the results read in tons and inch-tons.

Reading Charts.—The alignment-type chart, as used here, involves merely a suitable arrangement and numbering of logarithmic scales, such as are used in the slide rule, to suit the formula and a representative range of values. Thus in a multiplication it is only necessary to lay a rule or other straight edge across the chart coinciding with given values on two scales, and read their product on the third scale. Where a number of values must be combined, the number of scales must be increased to suit. Constants and conversions are taken care of in laying out the scales so that no attention need be given to them.

Examples, followed through with dotted lines and arrows, are shown on each chart to illustrate the method of reading it. Thus, in Chart I, the example shows the load required to punch a 4½-in. blank out of No. 18 gauge (0.050 in.) brass having a shearing resistance of 40,000 lb. per sq. in. The straight edge is placed across the value 4.5 on the diameter scale and 0.05 (or No. 18 gauge) on the metal thickness scale. The point at which the straight edge crosses the center line or pivot scale is marked or noted. This point and the value 40,000 on the shearing strength scale serve to locate the straight edge for the final reading, which gives 15 tons on the shearing pressure scale as the answer. A celluloid triangle is recommended for reading the charts, as figures and notations are visible through it. Even a piece of paper may be used, however.

Safety Factors.—Some allowance must be introduced into the use of almost any chart or formula to compensate for intangibles, omissions and accidents. Such an allowance has been facetiously called the "factor of ignorance," a term which has some justification, for if the intangibles were definitely known they might be included in the original formula.

In metal-working operations some variation in thickness, temper and constitution of the metal must always be expected. In the equipment, friction and inertia losses may be considerable, and there are often stripping, counter-

balancing or blank-holding pressures which may or may not have to be added to the working loads, and which are frequently relatively large. Certain classes of fine and delicate tools require oversize machines so that frame deflections, wear of moving parts, etc., will not reduce the tool life. Rugged tools for flattening, stamping, coining and otherwise squeezing or "hitting home" almost always make it essential to allow excess capacity, as small differences in metal thickness or in press adjustment cause large differences in working pressure.

Tool maintenance and operating conditions will have an effect upon resultant loads. Fig. 38 showed the result of different tool clearances. Dull cutting edges, improper shear, roughened drawing surfaces and lack of lubricant, especially in drawing, all add to the load. Double blanks are the most frequent menace in the matter of accidental overloads.

Such considerations as these prompted Professor L. P. Breckenridge to call for the addition of the factor J, for "judgment," in most engineering formulae. Whatever it is called, an allowance must be taken into consideration in the use of many theoretical formulae.

Blanking or Shearing (see also Chapter III).—The most common group of metal-working operations is that which includes blanking, piercing, parting, shearing, notching, trimming, perforating, etc. In all these cases the metal is stressed in shear between approaching cutting edges until a fracture occurs. The equipment and maintenance engineer may wish to arrive at the maximum blanking or shearing pressure required for his various tools, the effects upon this maximum pressure of shear on the punch or die (grinding one or the other at an angle), and the power or flywheel energy needed for the work.

Chart I is arranged from formula 2, page 34, to give blanking or shearing pressures in tons. Its limits are selected to cover the normal range of power press (and squaring shear) capacities. It is assumed that the tools are ground flat and parallel, and have ample clearance. Friction is neglected. The constant π for round work, and the conversion to tons (2000 lb.), are taken care of automatically in the scale arrangement. The area in shear shown on the center scale is incidental and usually unimportant, as this scale serves only as a pivot point between the first and second settings of the straight edge. The method of reading this chart has been described above.

The shearing strengths indicated at the left of the chart were taken from Table II, page 36. As suggested in that table and by curves A and C in Fig. 32, the shearing resistance rises as the metal is cold-rolled to the harder tempers or as it is strain-hardened in drawing or coining. Specific data on that subject are still meager, although the shearing resistance is always below the nominal ultimate tensile strength in a ratio which varies from around 1 : 2 or 2 : 3 in the annealed state toward 1 : 1 at the plastic limit.

As a flat punch progresses through a sheet of metal, it deforms the metal plastically to a point where the ultimate strength is exceeded and fractures start from the opposing cutting edges of the punch and die. If there is proper clearance between the tools, the fractures meet almost instantly and the fractured portion of the sheared edge appears quite clean, Fig. 22. If the clearance is not sufficient, the first fractures do not meet and secondary shearing takes place

with a characteristically irregular and ragged appearance around the edge, Fig. 23. When the cut is clean, a brightly burnished band around the edge of the blank indicates how far the punch had to penetrate before the fracture occurred.

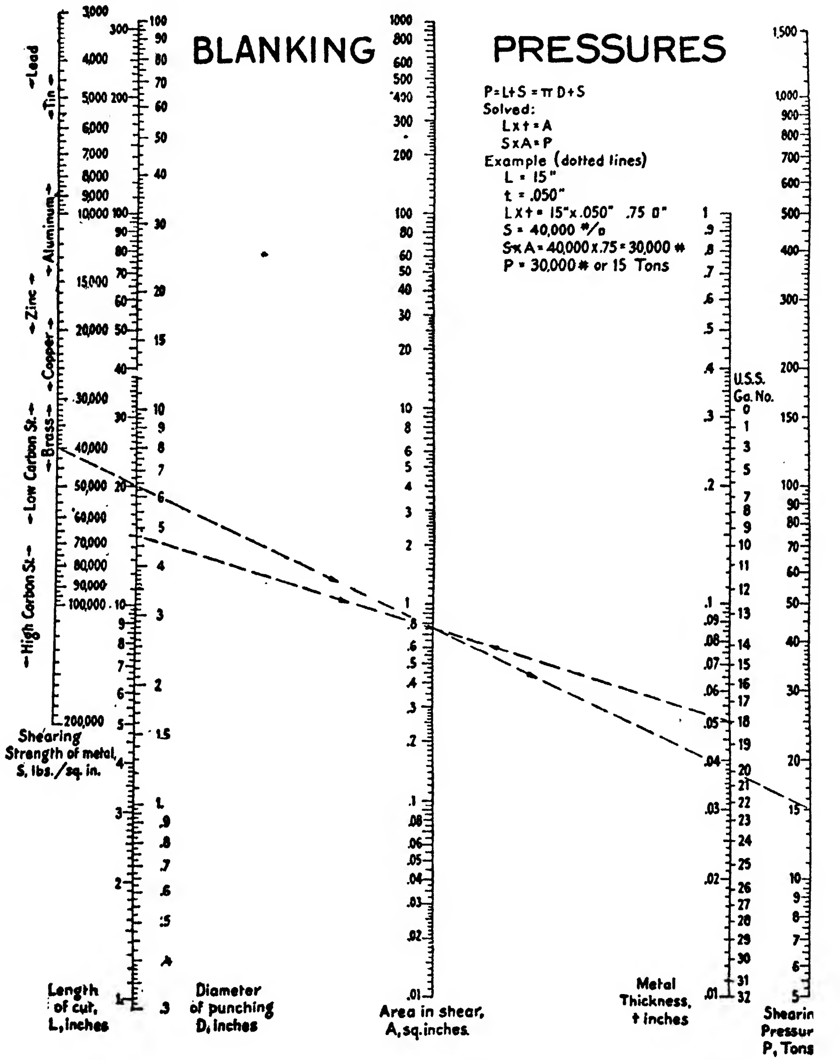


Chart I

This is of interest in connection with Charts II and III, as the work is entirely or nearly completed at this point.

The per cent penetration to effect shearing, as shown in Table II, comprises largely values obtained experimentally from tests performed in a recording Olsen

testing machine. Several typical curves are shown in Fig. 420. The clearance was ample for a clean cut in curves *a*, *b*, *c* and *d*, and the end of the curve indicates the point of fracture. Curves *e*, *f* and *g* show the effects of progressively reduced clearance upon *c*.

Figs. 28 and 29 illustrate diagrammatically the effect of shear upon the blanking load. The noun "shear" refers to grinding either the punch or the die at an angle, the other member remaining flat in order not to distort the product. The amount of the shear is the difference between the high and low points of the angular face, Fig. 28, even though the punch may be ground down both ways from one or more high points.

The effect of shear is clearly to reduce the peak load of blanking by shearing a little at a time instead of taking the whole cut at once. The total work done is not changed, being merely a lower pressure continuing through a longer time. Thus in either of the groups in Fig. 29 the area under the curves remains the same. A small amount of shear (less than the distance a flat punch must travel to effect shearing) does not appreciably reduce the load but does ease the dangerous snap-back, especially of C-frame presses, which occurs when the whole load is released instantly by the fracture. See Fig. 29.

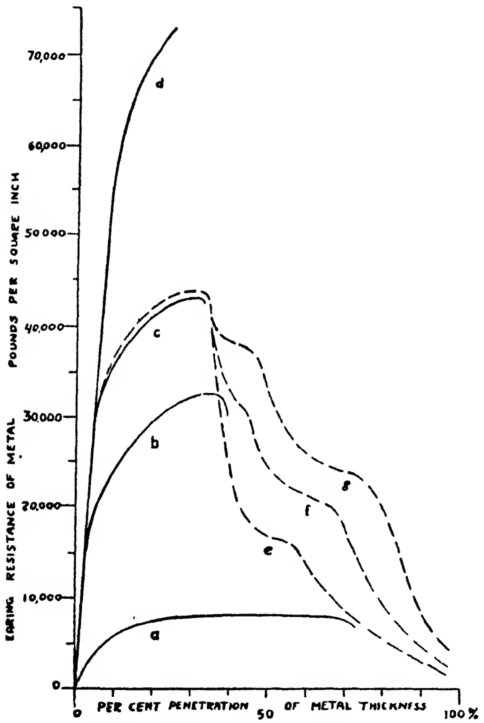


FIG. 420.—Blanking pressure curves for: (*a*) annealed aluminum, (*b*) dead soft cold-rolled steel (low carbon), (*c*) annealed 0.20 to 0.30 C steel, and (*d*) annealed high-carbon steel, having about 10 per cent metal thickness clearance. Dotted curves (*e*), (*f*) and (*g*) illustrate the effect upon curve (*c*) of clearances of about 8, 4 and 1 per cent respectively.

Chart II is designed for use in approximating the extent to which the total or maximum load is reduced by shear on the tools. In the case of ample clearance and a clean fracture, the result obtained is high as the calculation is based upon the assumption that the working pressure without shear is equal to the maximum pressure recorded, throughout the working distance. Reference to any one of the curves in Fig. 420 will show that this is not quite true. The

pressure rises gradually to the maximum and then usually falls slightly to the point at which the fracture occurs. The average pressure for the penetration distance, which would naturally be lower than the maximum pressure, would

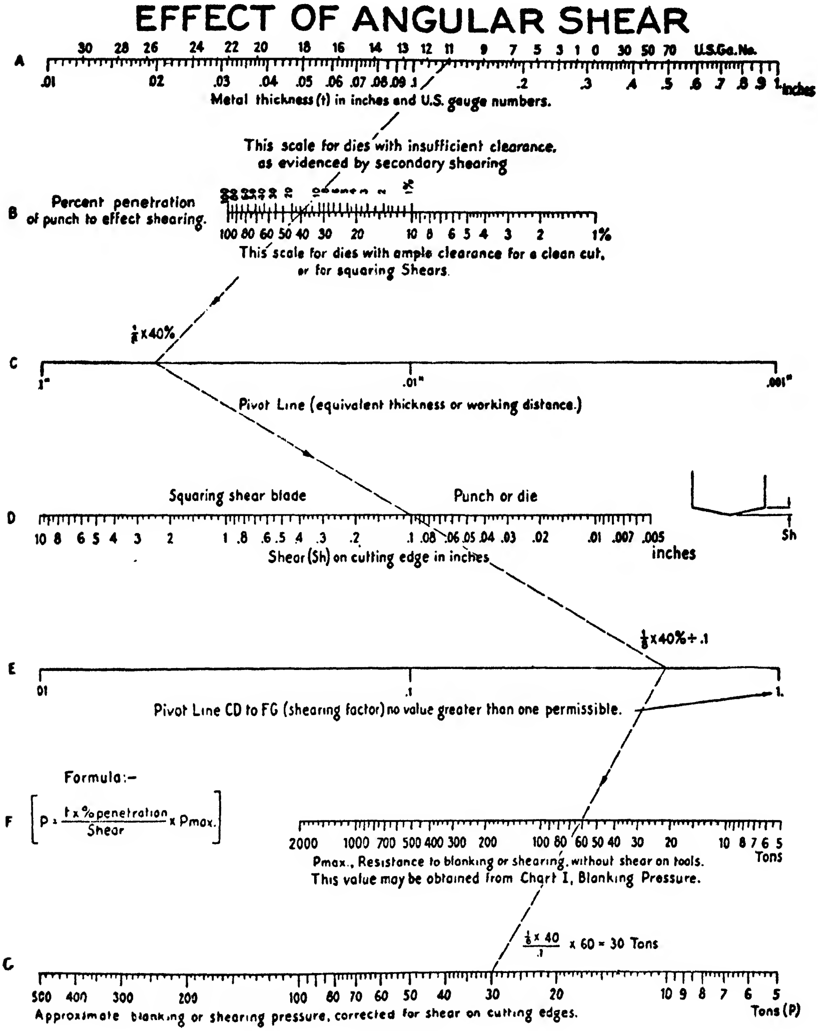


CHART II

give an accurate result. But an accurate pressure diagram is rarely available, and the chart is close enough for ordinary purposes. Note that it is always desirable to have considerable *excess press capacity* on blanking work for the sake of tools.

In the case of insufficient clearance in the tools and a ragged fracture, secondary shearing occurs so that the pressure curve does not drop sharply but continues as suggested by the dotted lines in Fig. 420. Several dotted curves are shown to indicate the manner in which secondary shearing increases as the clearance becomes less and less. The square root scale for per cent penetration is an arbitrary method of compensating for the effect of secondary shearing, but is ample, in the opinion of the author, to cover any ordinary cases. Usually, of course, the result will be high.

Chart II is read from the top down, and, as indicated by the example in dotted lines, the third and fifth lines are used only as pivot points for the straight edge. The somewhat empirical formula used is:

$$P = \left(\frac{t \times \%\ \text{penetration}}{\text{amount of shear}}\right) \times P\ \text{max.} \tag{41}$$

The thickness multiplied by the per cent penetration to effect shearing gives the actual working distance in inches. This divided by the amount of shear on the tools in inches gives the proportion of the length of the cutting edge which is actually working at any instant. See Fig. 28. This, multiplied by the maximum pressure (without shear) from Chart I, gives approximately the maximum working pressure. As noted at E on the chart, formula 41 does not hold unless the shear is sufficient to give a value less than 1 for the portion which is in parentheses.

In checking up power requirements or flywheel capacities, it is necessary to know the actual power absorbed in doing the work. In the case of shearing, this is properly the working distance multiplied by the average pressure, or graphically, the area under the pressure-distance curve, Figs. 27 and 420. As such curves are not easily obtained and therefore average pressure cannot be measured, we resort again to the approximate methods used above. That is, in *Chart III*, the maximum pressure (P, from Chart I) is used in place of average pressure, and the working distance is taken as the product of the metal thickness, t, and the per cent penetration, using two scales for the latter. Then the energy or work, W, in inch-tons is:

$$W = t \times \%\ \text{penetration} \times P \times 1.16 \tag{42}$$

The 1.16 is to include a 16 per cent allowance for machine friction. This can be only a general case, of course, as the arrangement and condition of machines vary widely.

It should also be noted that an allowance should be made for heavy stripper springs, when used, and for wall friction in pushing slugs through the dies, when there are long straight walls, as is occasionally the case.

In using Chart III, read thickness and per cent penetration first, to obtain the pivot point for the straight edge. Then set the straight edge on this point and the pressure value, to obtain the work.

Drawing and Reducing (see also Chapter VIII).—Power-press operations involving the cold drawing and redrawing of metal from flat blanks into cups,

pans and a multitude of other shapes are second only in breadth of application to the blanking and punching operations just discussed.

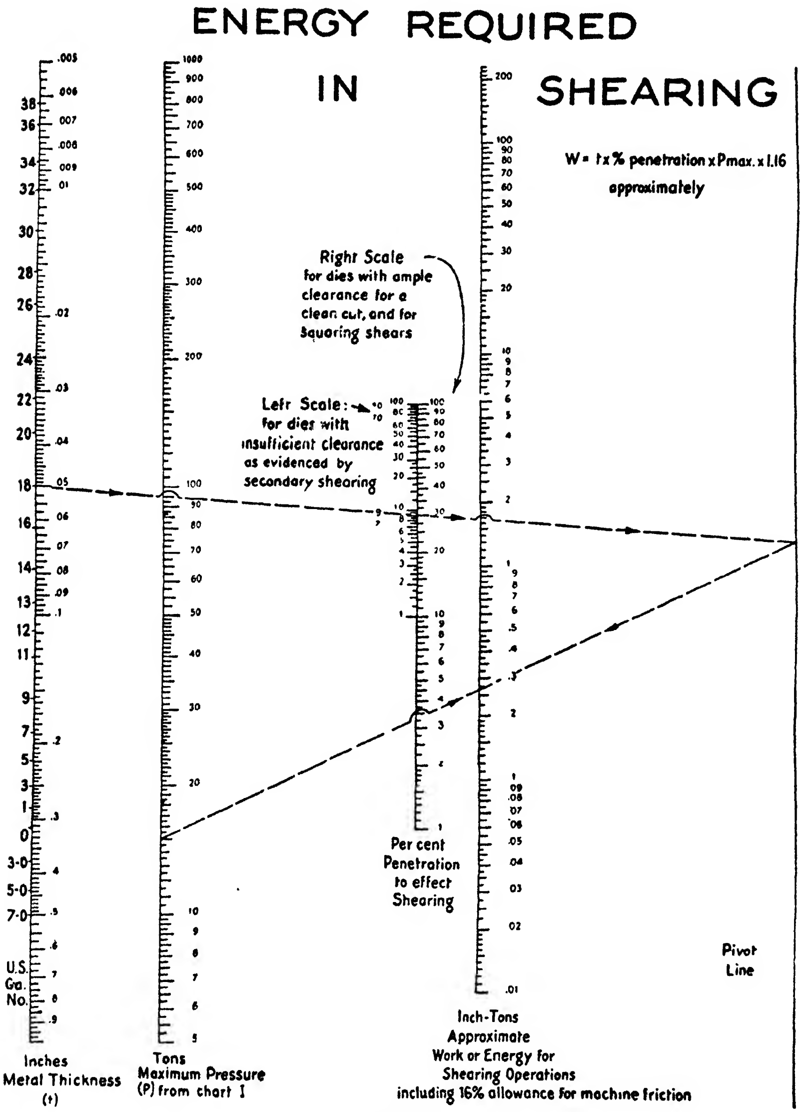


Chart III

The starting point in the drawing group is to compute the size of blank required to make the desired shell. For most purposes the shell is relatively thin,

and the bottom corner radius is small so that both may be neglected. The formula is then merely the equation of the surface area of the shell and the area of the blank:

$$\frac{\pi D^2}{4} = \frac{\pi d^2}{4} + \pi dh$$

in which D is the blank diameter, d the shell diameter and h the shell height. For slide-rule use this reduces to:

$$D = \sqrt{d^2 + 4dh} \qquad (25)$$

Neither formula adapts itself to a chart which is easily read, so that it seemed best to use the form:

$$\frac{D^2}{4} = d(h + \tfrac{1}{4}d)$$

In *Chart IV*, then, it is necessary to add one-quarter of the shell diameter to the height, for use on the left-hand scale as a starting point. That is quickly done, however, and it is then possible to set the other end of the straight edge at the shell diameter and read the approximate blank diameter on the center scale. An example is shown dotted on the chart for illustration. Table XXV, page 488, is based on the same formula and covers quite a wide variety of shell sizes.

If the metal thickness and bottom corner radius are relatively great, as shown in Fig. 144, so that these also should be considered, formulae 26 and 27 on page 162 should be used. The latter is really based upon figuring the volume of metal required rather than the surface area. Volume or weight is also the only proper basis for approximating shells which have been subject to severe ironing (reducing the wall thickness).

It is rarely possible to compute any blank precisely or to maintain perfectly uniform-height shells in operation, for the thickening and thinning of the wall vary with the completeness of annealing; the height of ironed shells varies with commercial variations in sheet thickness and the top edge varies from square to irregular, usually with four more or less pronounced high spots resulting from the effect of the direction of rolling on the crystalline structure of the metal. Thorough annealing, of course, should largely remove this directional effect. For all these reasons it is ordinarily necessary to figure the blank sufficiently oversize to permit a trimming operation. Common practice is to finish the drawing tools first and then correct the figured blank size by trial, before making the blanking die.

The trial method applies even more particularly to rectangular jobs than to round ones. The length and width of the blank can usually be approximated, as the sides are nearly straight bending. At the corners the drawing action cannot be compared directly with that in round shells as the unstrained side-walls act as a relief area. The developed corner for a rectangular shell blank, as found by trial, is not bounded by a radius but more nearly follows a 45° angle across the corner with a little radius at each end, Fig. 156.

Chart V is arranged particularly for convenience in approximating the number of operations in a series of reductions for a round shell, or for adapting stock

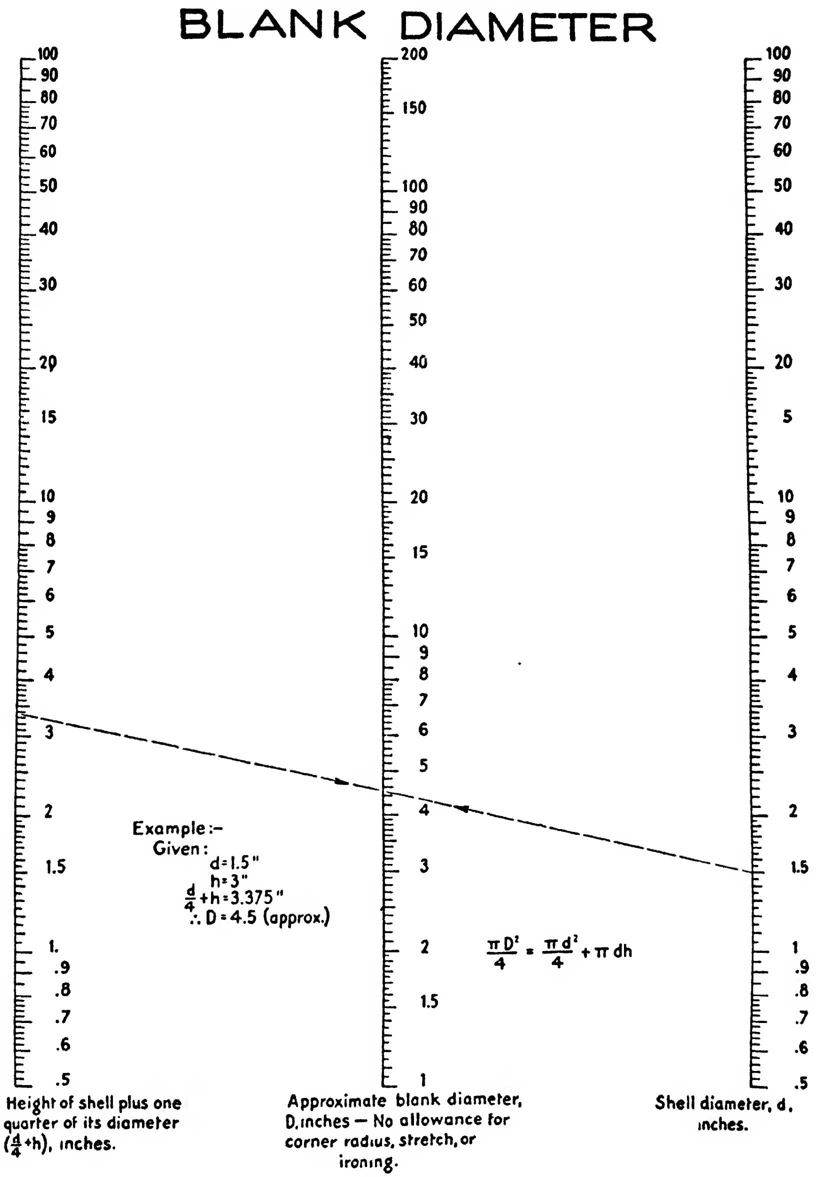

BLANK DIAMETER
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
2
1.5
1.
.9
.8
.7
.6
.5
200
150
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
2
1.5
1
100
90
80
70
60
50
40
30
20
5
10
9
8
7
6
5
4
3
2
1.5
1
.9
.8
.7
.6
.5
Example:–
Given:
d=1.5"
h=3"
$\frac{d}{4}$+h=3.375"
∴ D=4.5 (approx.)
$\frac{\pi D^2}{4} = \frac{\pi d^2}{4} + \pi dh$
Height of shell plus one quarter of its diameter ($\frac{d}{4}$+h), inches.
Approximate blank diameter, D, inches — No allowance for corner radius, stretch, or ironing.
Shell diameter, d, inches.

CHART IV

draw rings to the specific job. The scales on the chart are so laid out that it can be read progressively from left to right and then right to left, etc., as indicated by the bracket arrows. The example, shown in dotted lines, illustrates the selection of a series of operations for producing a $3\frac{3}{16}$-in. diameter shell from a 10-in. diameter blank. Following the dotted lines, note that the blank (d) is reduced 40 per cent in the first draw to a 6-in. diameter shell, which is reduced 30 per cent in the second draw to a 4.2-in. diameter shell, which in turn is reduced 25 per cent in the third draw to the required 3.18-in. diameter. This series is conservatively chosen for most cases and should cause no trouble. Trial will also show that the job might be done in two steps, assuming a limit 48 per cent reduction to 5.18 in. in the first step and a double-step single-action reduction of 38 per cent for the second, providing the metal is thick enough. Both of these would be troublesome operations to get going, however, and very close control of the material would be necessary.

Fig. 421 is offered tentatively as a means of determining the maximum reductions permissible under various conditions. It is an initial effort at so concise a form and may be open to modification. The top limit of 50 per cent reduction for a first operation seems to be substantiated both by practice and by the theory concerning the strains set up in drawing. The 30 per cent limit for double-action reductions is dictated by practice and is modified by friction, corner radii and whether the blank-holding face is flat or at an angle to the shell wall. The 25 per cent limit for single-action reduction is taken from practice and depends upon the formation of wrinkles. Two-step dies in single-action reducing, Fig. 148*E*, are not especially common but seem to reduce the tendency to wrinkle and permit a higher limit.

The relative thickness of the metal is the factor which determines whether or not a blank-holder is necessary or possible, so that in Fig. 421 the basis for comparison is t/d, or blank thickness divided by blank diameter. The lines which mark the boundaries of single- and double-action work are necessarily not sharply defined, as much depends upon the radius or angles of various parts of the dies as well as upon the material itself.

In order to compensate to a certain extent for strain-hardening of the metal, some die designers prefer to use a descending series of reductions where a number of operations are to be performed without annealing. Thus for double-action reductions the successive steps may be 30, 25, 20, 16, per cent, etc. For single-action redrawing the series might start at 25 per cent reduction. For very thin material either series would start lower.

The upper dotted line on Chart V indicates that the total reduction from 10 to 3.18 in. amounts to 68 per cent. This is a measure of the amount of cold-working to which the metal is subjected, and may be used in judging the need for annealing. Records are available showing total reductions of 59 per cent between anneals in best quality drawing steel, Figs. 125 and 126.

At the top of Chart V is a scale for comparing various common methods of describing reductions, as a means of reconciling factors used in different plants. Thus the relation between a 10-in. diameter blank and a 6-in. diameter shell may be described as a 40 per cent reduction of the blank, a shell diameter 60

per cent of the blank diameter, or a blank 1.66 times the shell diameter. The author prefers per cent reduction as a measure of cold-working.

Note:—Organic plastics, papers, and other mixtures low in relative tensile strengths, are limited to much smaller reductions per operation than is shown for the metals.

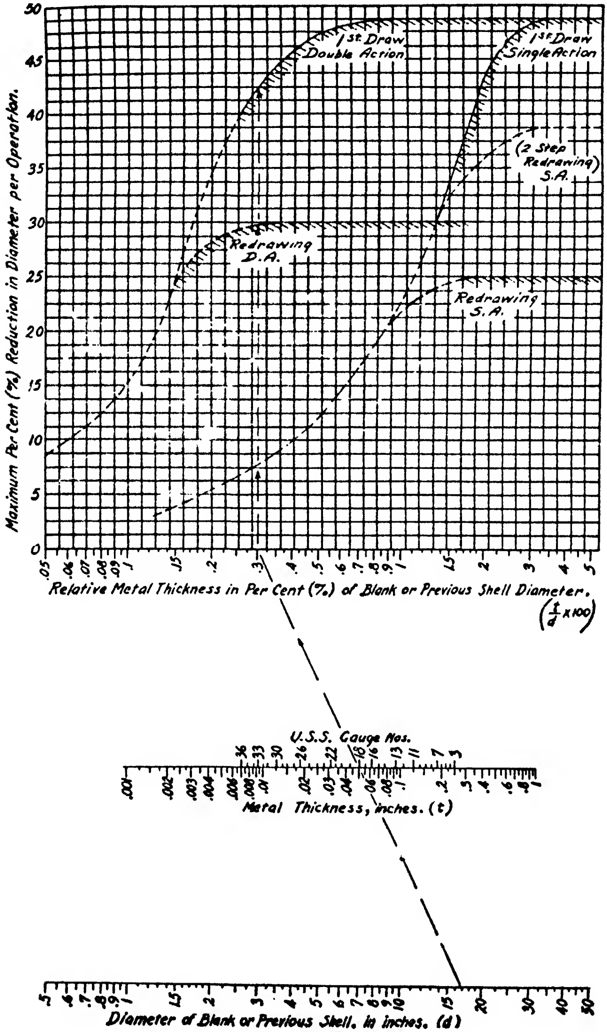


FIG. 421.—Tentative chart for determining maximum reduction (in diameter) by various methods. Dotted lines seem to be proving unduly conservative.

Chart VI, for computing quickly the maximum working pressure in drawing operations, is based upon a free draw with sufficient clearance so that there is no ironing or burnishing, and upon a maximum reduction (nearly 50 per cent). Formula 21, page 155, gives actually the "load to pull the bottom out," or the

tensile strength near the bottom of the shell. This must exceed the drawing load in a successful draw, or tearing would result. Lower pressures for shallower shells are discussed in connection with formula 22. If there is ironing, wall friction may carry a considerable part of the added load. Other combinations of operations, such as blanking and drawing, drawing and piercing, drawing and

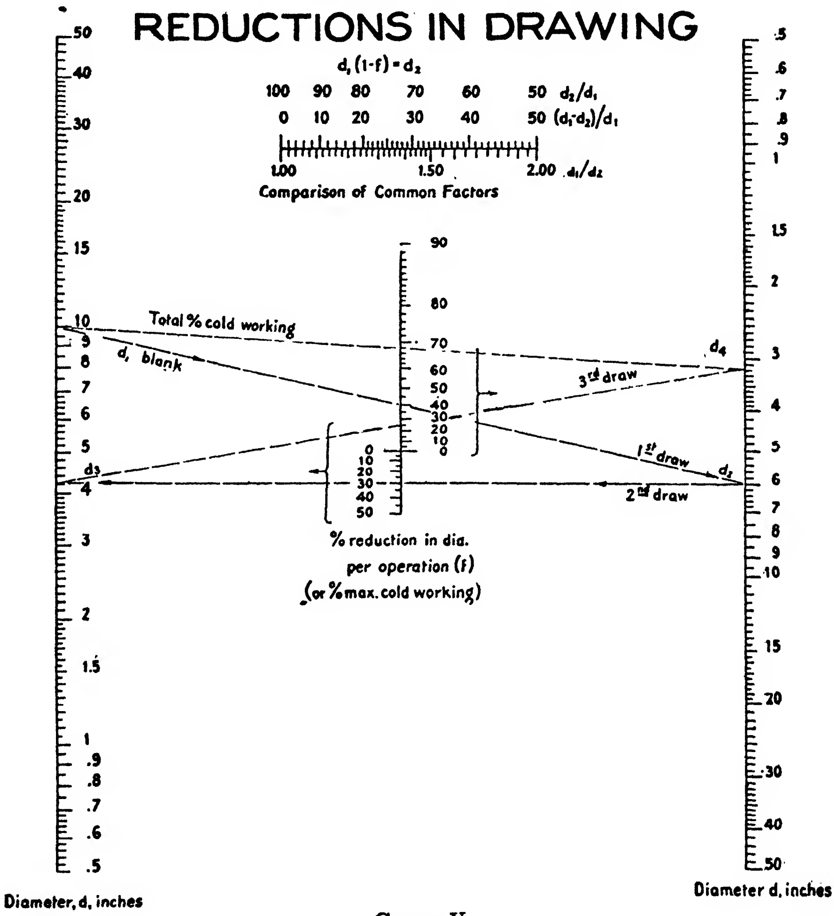


CHART V

stamping, etc., require that the added operation be figured separately, though it need not be added if it occurs before or after the actual drawing period.

In using the chart, the outside diameter of the shell is close enough unless the wall is relatively thick, in which case it is better to use the mean diameter ($OD - t$) or ($d - t$), Fig. 144. Following the example shown by dotted lines, note that a line between the diameter, 10 in., and the wall thickness, ⅛ in., on the two inner scales, gives the wall cross-section (nearly 4 sq. in.) on the

center scale. This value, and the tensile strength of the material (deep drawing steel) on the extreme left scale, give the maximum drawing pressure on the right. See stress at various shell depths in Fig. 137.

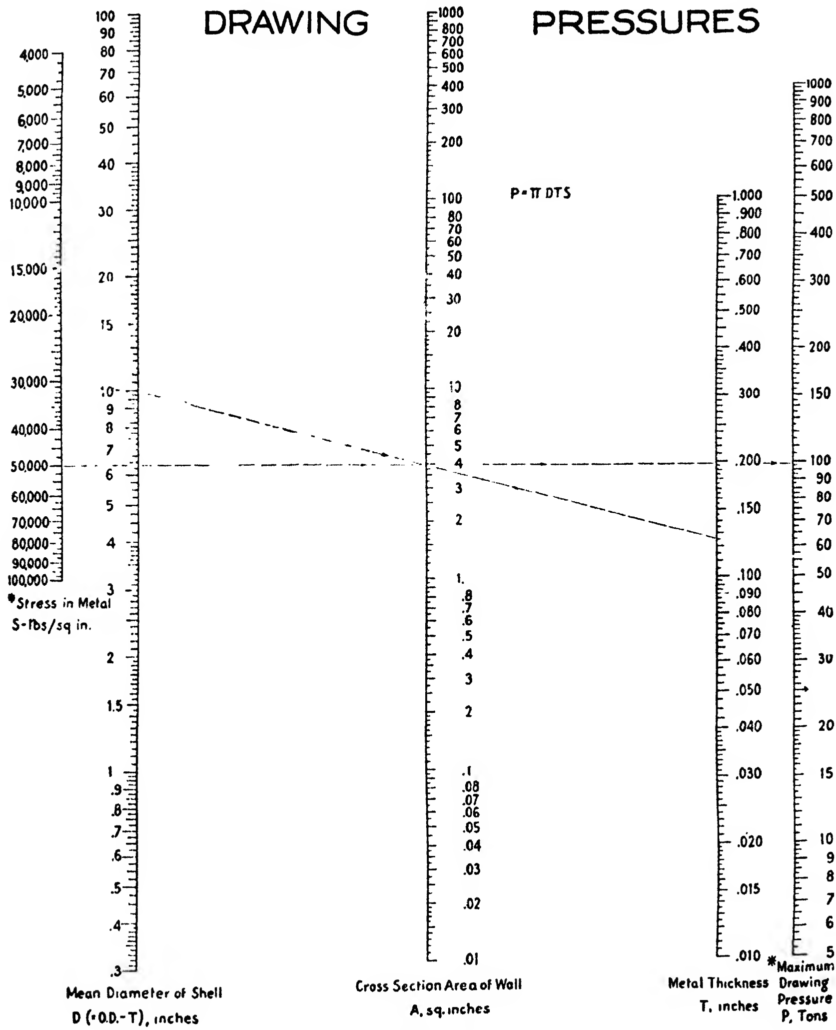


CHART VI

The work done in a drawing operation, or the energy required to do it, is roughly the product of the drawing pressure (in tons) and the depth of draw (in inches) giving work (in inch-tons). In actual practice the work requirement is materially less than this, owing to the gradual rise of the pressure. The true

measure of the work done is, therefore, the area under the drawing pressure curve. This has been noted down for each draw, in Fig. 137, using inch-pound units which may be easily converted to inch-tons. For use in later check-ups of flywheel capacity and motor drive, a formula for work, W (inch-tons), may be expressed:

$$W = P \times h \times C \tag{24}$$

in which the corrected drawing pressure, P (tons), and the shell height, h inches, have occurred before. The constant, C, which is not included in the chart, may be taken at 60 to 80 per cent (0.60 to 0.80) to allow for the gradual rise of the pressure.

Drawing operations are performed both in double-action toggle and cam presses and in single-action presses equipped with pneumatic, spring or rubber drawing attachments. In toggle-press construction the blank-holding pressure is taken on rock shaft bearings in the press frame so that the crankshaft sustains only the drawing load. The other types take both the drawing and the blank-holding loads on the crankshaft, and allowances should therefore be made in computing press capacities. For deep drawing of round work the blank-holding pressure should be under 30 or 40 per cent of the drawing pressure. For large rectangular work the drawing load is relatively lower than for round work, but the allowance for blank-holding may run as high as 100 per cent. In stretching shallow shapes such as casket tops the metal must be gripped tightly around the edge, and blank-holding pressure may be two or three times the relatively low drawing load.

Ironing, Coining and Forging (see also Chapters X and XII).—This group of operations is distinguished by the fact that the primary working stress is compressive, and in all but the first case the blank or slug is squeezed directly between the punch and die. The operations included in this group are ironing, stamping, sizing, swaging, coining, extrusion and press forging.

Ironing, which is the reduction in thickness of drawn shell walls by pulling them through tight dies, is related to both shell drawing and wire drawing. It is done to obtain a wall which is thin compared with the shell bottom, to obtain a uniform wall, or a tapered wall as in cartridge cases, or merely to correct the natural wall thickening toward the top edge of a drawn shell. In this last case the amount the wall thickness will increase in drawing must be discovered.

Chart VII is arranged to show approximately the natural change in thickness accompanying a change in diameter. The results which it gives apply to the upper edge of drawn shells, since the wall thickness tapers from a maximum at that point to a minimum at the bottom corner, where it may be as much as 10 or 15 per cent less than the original metal thickness. Even at the top edge the metal thickness is likely to be a little less than the theoretical thickness given by the chart because of the thinning effect of bending over the drawing edge. A sharper radius or a deeper draw increases this thinning effect.

Chart VII is always read from left to right, drawing a line between the original diameter (of blank or shell) and the final (shell) diameter, on the two inner scales, to obtain the maximum per cent reduction or expansion on the center

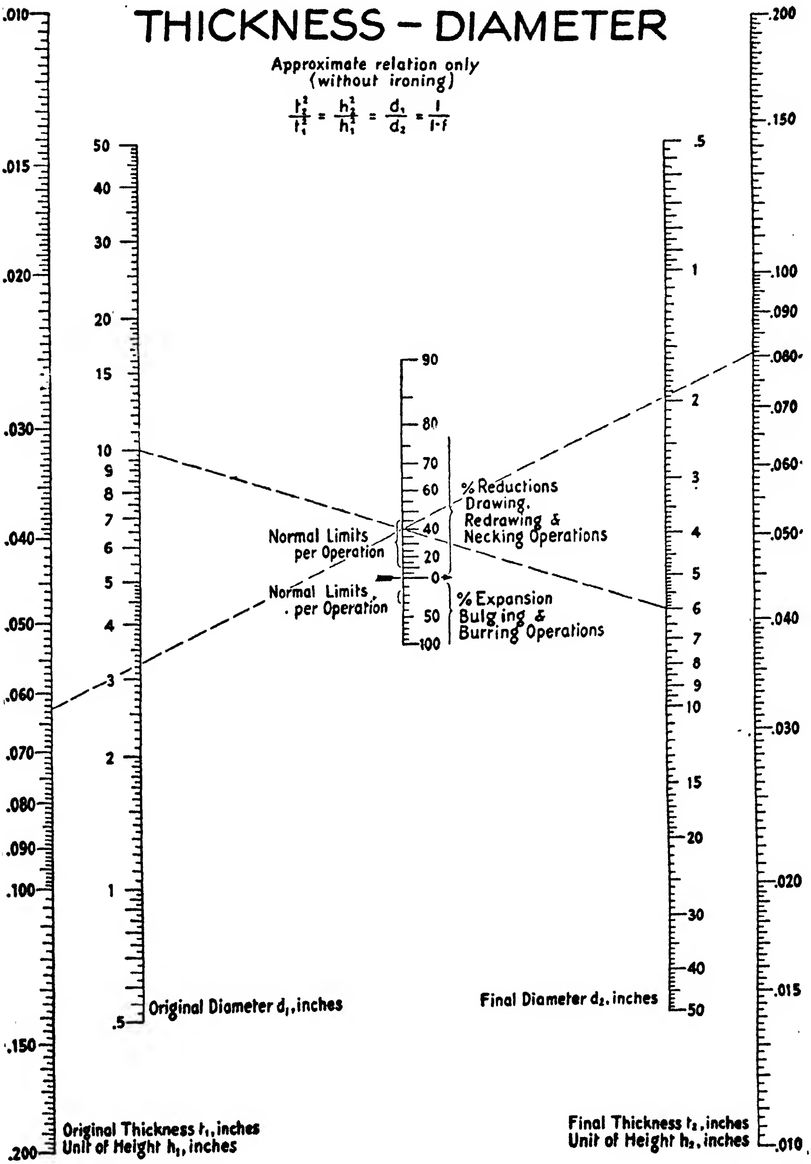

THICKNESS – DIAMETER
Approximate relation only
(without ironing)
$\frac{t_2^2}{t_1^2} = \frac{h_2^2}{h_1^2} = \frac{d_1}{d_2} = \frac{1}{1-f}$
Normal Limits per Operation
% Reductions Drawing, Redrawing & Necking Operations
Normal Limits per Operation
% Expansion Bulging & Burring Operations
Original Diameter d_1, inches
Final Diameter d_2, inches
Original Thickness t_1, inches
Unit of Height h_1, inches
Final Thickness t_2, inches
Unit of Height h_2, inches

CHART VII

scale. A second line through this point, and starting from the original metal thickness on the left-hand scale, will indicate the approximate maximum wall thickness at the upper edge of the final shell. An example is indicated in dotted lines. It is noted on the chart that this is based upon a draw with sufficient clearance between the punch and die so that there will be no ironing.

Then if the clearance between punch and die is made equal to the metal thickness (0.0625 in. in the example) there is an ironing load added to the drawing load (sufficient to remove 0.0805 in. − 0.0625 in. = 0.018 in.). If a parallel wall is desired, it will be necessary to iron down to the thickness of the thinnest part of the wall, which is appreciably less than the original metal thickness, depending upon the sharpness of corner radii and the severity of reductions.

Chart VIII offers a convenient means of approximating the pressure required in ironing. Referring to the example shown in dotted lines, note that the two inner scales are used first, to establish the pivot point on the center scale. Thus a shell ironed to a finished diameter of 4 in., with a displacement of 0.010 in. of the total metal thickness, will require an ironing pressure of about 3.8 tons, assuming that the material is a mild steel not severely strain-hardened and therefore offering a compressive resistance of about 50,000 lb. per sq. in. This must be added, of course, to the drawing or redrawing load figured separately from data just given. The formula used, which differs from the more accurate formula 30, for simplicity is:

$$P = 1.2\pi \times d \times i \times S$$

in which P is the approximate maximum pressure required in tons, d is outside diameter after ironing in inches, i is the reduction in wall thickness in inches, and S is the compressive resistance of the metal under existing conditions of strain-hardening, in pounds per square inch. A 20 per cent allowance for surface friction in addition to the work of coining is included. This is an arbitrary figure which should cover well-polished dies and suitable lubrication. Lack of lubricant, tool-mark rings on the dies or picking up on the surface will increase the friction load to a much larger figure.

If the wall of a shell is ironed thinner by the same amount for the entire length of the shell then the work done is approximately the product of the length of the shell or of the ironed surface and the pressure required for ironing from Chart VIII. That is:

$$W = P \times l \tag{31}$$

in which work, W, is in inch-tons; pressure, P, is in tons; and length, l, is in inches. This is the case in most cartridge case operations, Fig. 153. If a reducing operation accompanies the ironing, then the drawing pressure should be added to the ironing pressure.

If the ironing operation is merely to correct the natural changes in wall thickness due to drawing and reduces the thickest portion near the top of the shell to equal the thinnest portion near the bottom, the average ironing pressure will equal about half the maximum, and the formula will be:

$$W = 0.5P \times l \tag{31a}$$

Among the direct compression or squeezing operations, including stamping, sizing, swaging (or forging), coining and extrusion, the working pressure required is based upon the plan view area or "projected" area of the job and the compressive resistance of the metal. The resistance varies with the relative amount

PRESSURE REQUIRED FOR IRONING

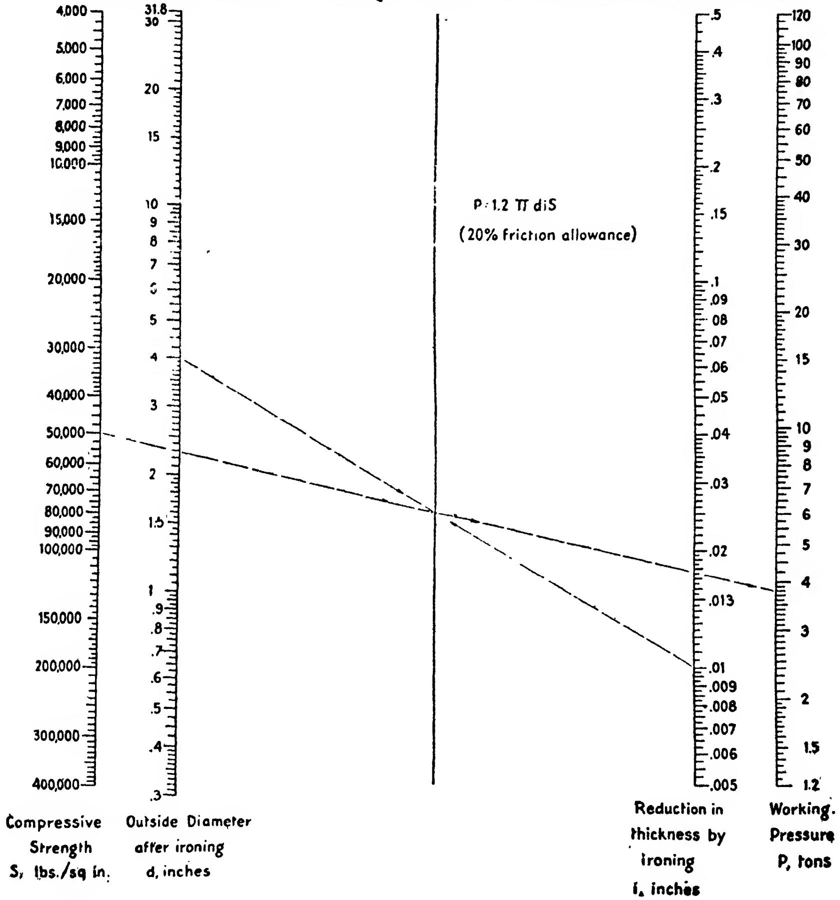


CHART VIII

of flow and freedom of flow of the characteristic operation as well as with the material and the amount of cold-working (strain-hardening) which it has undergone.

Chart IX involves a simple multiplication: pressure or press capacity, P, in tons, equals the product of the projected area of the piece, A, in square inches, and the compressive resistance of the material, S pounds per square inch, in

which proper allowance must be made for the character and arrangement of the job.

$$P = A \times S \tag{43}$$

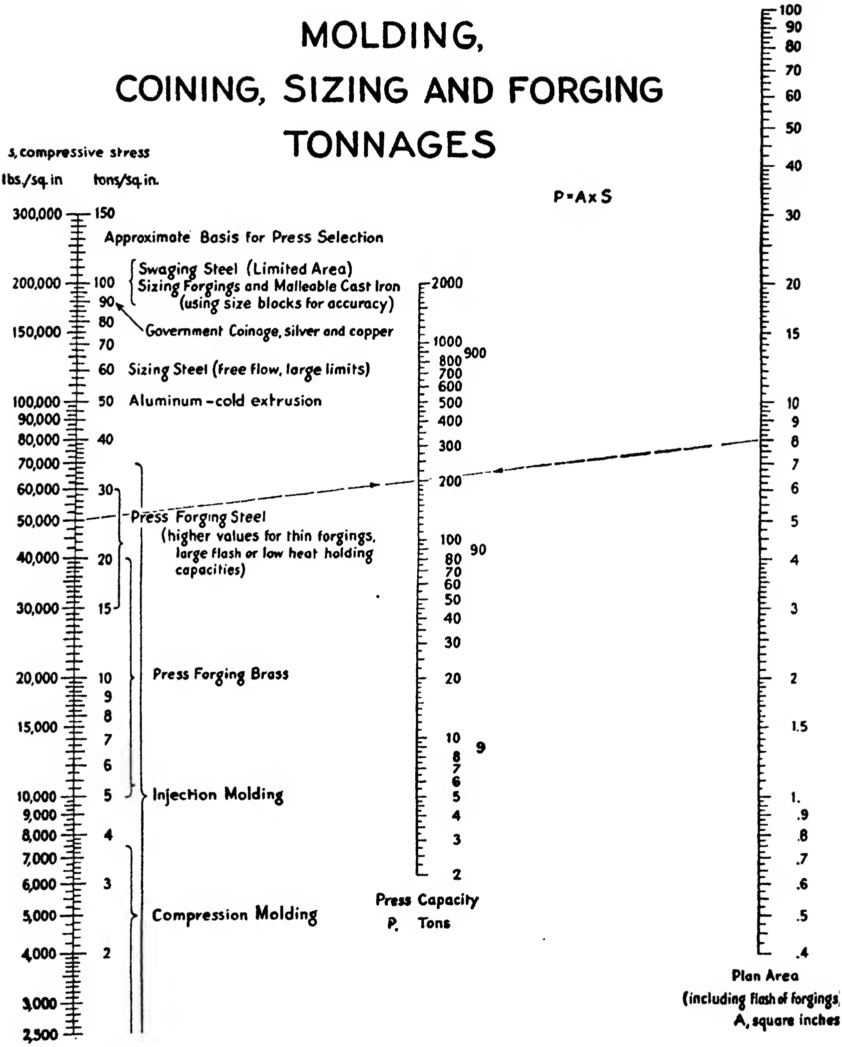


CHART IX

The press capacity may also be determined from direct tests with the finished tools, performed in testing machines or hydraulic presses with suitable gauges. In such cases it is conservative practice to double the test pressure in selecting the mechanical press owing both to its much greater speed and to the inflexible character of a good stiff machine, a factor which contributes much to the accuracy

of the finished product. In selecting extrusion presses based on test results the experimental pressures should be more than doubled, as the increased speed of flow through the small orifice around the punch greatly increases the working load.

Somewhat less conservative ratings may be used with assurance for many operations of the squeezing group by arranging the presses with hydro-pneumatic overload-relief cushions built into the press-bed. Such combination machines, Figs. 203 and 246, take care of variations in volume of material, double blanks, cold slugs (in forging), etc., without sacrificing any of the speed, operating and maintenance advantages of the mechanical equipment.

Working area is the projected area, in the plan view, of all surfaces of a job which are in contact with the die surfaces at the completion of the squeeze. Thus in Fig. 422 at c note that the forging is relieved at two points to reduce the squeezing area; at h the die is relieved for the same purpose; and at f the area of the piece is increased by the area of the portion of the flash which is being squeezed.

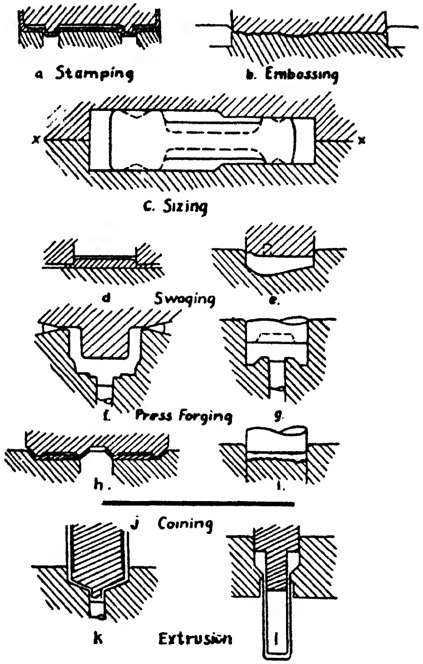


FIG. 422.—Typical operations of the squeezing group illustrating also restriction of metal flow.

Fig. 422 is prepared primarily to distinguish certain typical operations and to illustrate differences in the freedom of flow of the material. Considerable judgment must be exercised in this connection in estimating the surface pressure which may be built up in completing the operation.

Stamping and embossing (at a and b), in which the original thickness of the sheet is unaltered except by the relatively mild strains of bending and stretching, may be very easy operations, hardly belonging in the squeezing group. This is particularly true in case a, where the die is relieved above and below so that it cannot strike solidly at any point. The operation is therefore practically drawing and may be figured, for steel, at 15 to 20 tons per square inch of cross-section along each line of the design. In case b the die "hits home" over the entire surface, but a sharp impression may be obtained with a relatively low pressure as the operation is intended to be bending and not squeezing. A little carelessness in set-up, however, or an oversize blank will greatly increase this

pressure. In fact, it may actually rise several hundred per cent, as the very large area relative to the metal thickness makes it almost impossible for the metal to flow out.

Sketches *e*, *g* and *i* in Fig. 422 illustrate other " closed " dies in which dangerous pressures are possible if care is not exercised. In the sizing operation at *c* the metal is entirely free to flow, but the die comes together on solid contact faces *x*, in order to make the accuracy obtained less dependent upon the thickness and hardness of the original forging. Such surfaces should usually take at least as much pressure as the forging itself. Presses for this work are often selected on a basis of 100 tons per square inch, though the actual pressure on the surface of the forging may not exceed 25 or 30 tons per square inch. In swaging or cold-forging steel (422*d*) the contact surfaces are usually unnecessary, but the pressures are higher on account of more severe working of the material. Accordingly, large areas and closed dies (422*e*) are out of the question in working steel, though practical, with care, for copper and other softer metals.

Coining (422*i*), in which metal is forced to fill an impression (usually) in a closed die, is limited to the softer metals and is usually figured for safety at about 90 tons per square inch.

Fig. 422*k*, typical of collapsible tube extrusion work, is limited to tin, lead and some pure aluminum work. Fig. 422*l* is somewhat less severe on tools and takes in (cold) copper extrusion. General figures of 50 to 100 tons per square inch cover most cold-squeezing operations with safety and represent about the maximum that present tool steels will stand.

Hot-forging pressures are figured conservatively at about a third of cold operations, although proper forging heats often bring the actual pressures relatively much lower.

In figuring energy or work (average pressure times working distance), in squeezing operations, the distance the punch travels from its first contact with the slug or blank to bottom stroke includes the amount the metal is moved and the amount of deflection in the press and tools (although part of the energy required to stretch the machine may be returned to the system, depending upon speed and friction relations). The working pressure will begin at the elastic limit of the material times the area of contact and will rise gradually as the material strain-hardens and the contact area increases. In the case of closed dies there is likely to be a further sharp rise when the die fills, its duration and extent being determined by the amount necessary to stretch the press to get over bottom center. The material, of course, is practically incompressible.

Press Selection.—After determination of the pressure in tons and the work in inch-tons required to do a given blanking or forming job, it is necessary to select a suitable press equipment. This involves consideration of:

The strength of the press, or its tonnage capacity;
The energy available for work, or flywheel capacity;
The speed of operation, or crankpin velocity;
The size of motor, or power requirement.

Here, again, general formulae, which are as satisfactory as possible, are offered with the warning that they be used with a conservative margin for safety, to cover many small variations in proportion and modifying influences which cannot be covered in so limited a discussion.

Tonnage Capacity.—Power-press builders have, in general, avoided placing definite tonnage ratings on their machines. The reason is indicated in part by Fig. 423. There are shown four machines of about the same normal tonnage rating, photographed to approximately the same proportion to indicate the wide disparity in overall dimensions. The difference is principally in stroke and working distance to suit different classes of work. The small coining press with a 1½-in. stroke will work through, say, ⅛ in. The forging press has a 4-in.

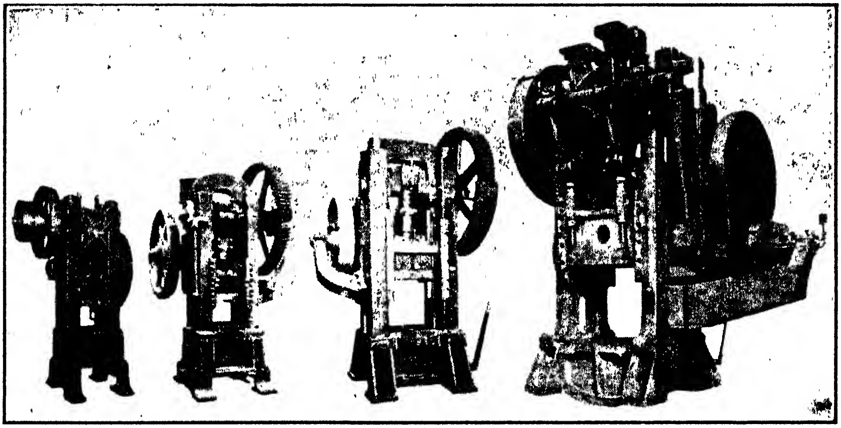


Fig. 423.—How big is a 250-ton press? Here are four geared, single crank, tie-rod frame presses of that capacity weighing respectively 12,000, 24,000, 33,000 and 145,000 lb. These are photographed to about the same scale.

stroke and 1½-in. working stroke. The general utility press has a 10-in. stroke and, say, 4-in. work stroke. The toggle press has a 28-in. stroke and 13-in. drawing stroke. The motor requirements will go up in general in proportion to the size, stroke and working distance.

Chart X is based upon the fact that if presses are similarly proportioned for a range of work the crankshaft may be taken as the index of tonnage capacity. There has been a tendency to underrate small presses and overrate large presses in line with an opposite tendency in the estimation of jobs. The difference has been blamed, without apparent justification, upon speed of operation.

If crankshafts of a given type are designed to about the same proportions, and their dimensions are reduced to terms of the shaft diameter, d, at the main bearings, as in Fig. 424a, the bending strength of the crankshaft at the center of the pin and the combined bending and torsion load at the side of the slab reduce to formulae for the pressure capacity P in terms of a constant and the shaft diameter squared, i.e.: $P = Cd^2$. The constant varies according to the

type and stroke of shaft. The method of analysis used has been checked against actual bending tests.

A series of constants for different shaft conditions is given in Table XXIV. These are based upon the bending strength of about a 0.40 C steel stressed to its elastic limit in fatigue. This limit is taken at 28,500 lb. per sq. in., and there is no so-called factor of safety except in the case of the eccentric type shaft, Fig. 424*d* and *g*, which is subject to shear rather than bending.

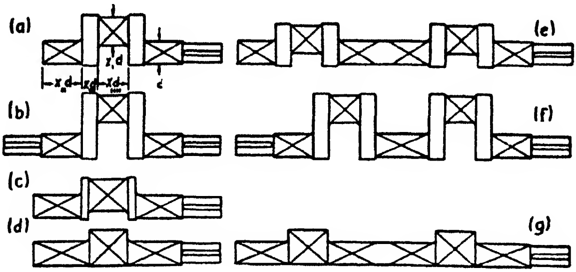


FIG. 424.—Single- and double-crank type, semi-eccentric type and eccentric type, single and twin drive shafts.

TABLE XXIV

PRESS SHAFT CAPACITIES

(Constants for Chart X)

Press Stroke in Terms of Shaft Diameter	$0.5d$	$0.75d$	$1.0d$	$1.5d$	$2d$	$2.5d$	$3d$
Type of Shaft	Constant C in formula, $P = Cd^2$						
Single crank with same diameter pin and bearings	.....	.....	2.8				
Single crank, single drive, oversize crankpin	.....	.....	3.5	2.7	2.2	1.8	1.6
Single crank, twin drive, oversize crankpin	.....	.....	.....	.....	3.5	3.0	2.7
Double crank, single drive, oversize crankpin	.....	5.4	4.4	3.2	2.5	2.2	1.7
Double crank, twin drive, oversize crankpin	.....	.....	.....	5.4	4.4	3.7	3.2
Single eccentric, single drive	4.1	3.6					
Single eccentric, twin drive	4.4	4.3					
Double eccentric, single drive	6.8	5.5					
Double eccentric, twin drive	8.1	7.2					

PRESS CAPACITIES

See also Table XXX, p. 514.

Note: This chart should be used with discretion. The center scale gives *maximum* press ratings which should not be exceeded. They should often be substantially reduced depending upon the nature of work being done.

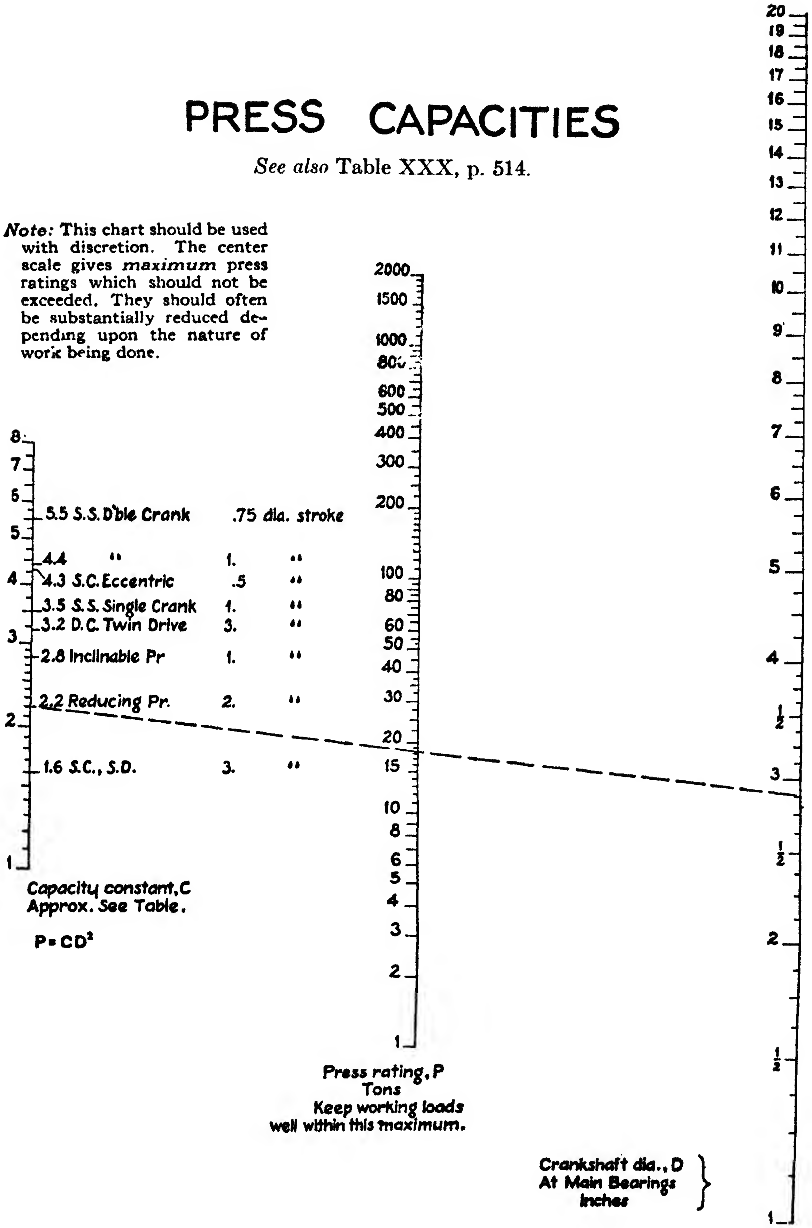


CHART X

In Fig. 424 the three basic shaft constructions are the crank type (*a*) used up to strokes of three diameters (stroke = 3 × shaft diameter *d*), the semi-eccentric type (*c*) for strokes up to about one diameter, and the full eccentric type (*d*) which is the stiffest but is limited to strokes of half the shaft diameter or a little more. These three are all shown with the single-drive arrangement, that is, a driving gear or wheel on one end of the shaft. The torsional load on a shaft is usually less than the bending load, but for long strokes there is an advantage in dividing the torsion by driving from both ends of the shaft as shown at *b* and *f*. The extent to which twin driving affects the tonnage capacity of a shaft may be seen by comparing ratings of similar single and twin drive shafts in Table XXIV. Values in the table are figured at midstroke, but do not take into consideration the gearing or the rest of the drive.

In using Chart X, select a suitable shaft constant from Table XXIV for the left-hand scale, take the shaft diameter on the right-hand scale and read the maximum tonnage on the center scale with a straight edge. C-frame press ratings should usually be more conservative than those for straight-sided presses. Strokes of two and three diameters (2*d* to 3*d*) indicate reducing or drawing presses which are rarely loaded to capacity except perhaps for a bottom bead stamping operation at the end of the stroke.

Flywheel Energy.—A press frame and shaft may be amply strong, but if the machine lacks sufficient flywheel energy or driving power for the job, it will stall. Thus, for a greater working distance and for faster operation, more energy and power must be provided. Strength or pressure is measured, for our purposes, in tons. *Energy*, which is (average) *pressure* or force *multiplied by* the *distance* through which it must be exerted, is measured in inch-tons. *Power*, which is the amount of *energy* to be supplied *in a given time*, is measured in horsepower. To put it another way, strength resides in the frame and shaft, stored energy in the flywheel and power in the motor.

Blanking operations are completed in a very brief portion of the press stroke or cycle. The flywheel instantly supplies (practically) all the energy required, by its resistance to being slowed down. The motor may then take the rest of the press cycle to restore the lost energy to the flywheel by bringing it back up to speed.

Drawing operations take a considerable part (up to ¼) of the press cycle. The time is sufficient for the motor, at say 100 per cent overload, to share with the flywheel a considerable part of the work.

For intermittent operation, 20 per cent is arbitrarily considered the maximum the flywheel may be slowed down in drawing energy from it. For continuous operation 10 per cent is considered the limit because of the shorter period to restore it.

In *Chart XI* the inertia formula has been arranged for press flywheel use:

$$E = \text{RPM}^2 \times D^2 \times W/5{,}250{,}000{,}000 \tag{44}$$

in which the energy E, available at 10 per cent slow-down (in inch-tons), is obtained from the RPM, diameter D in inches, and weight W in pounds, and a

suitable constant which includes the necessary conversion factors. In reading this chart place a straight edge to connect values for the speed and diameter of the flywheel on the two inner scales, and mark where it crosses the center or pivot line. Taking this point and the flywheel weight on the left scale, the straight edge will indicate flywheel energy available on the right-hand scale.

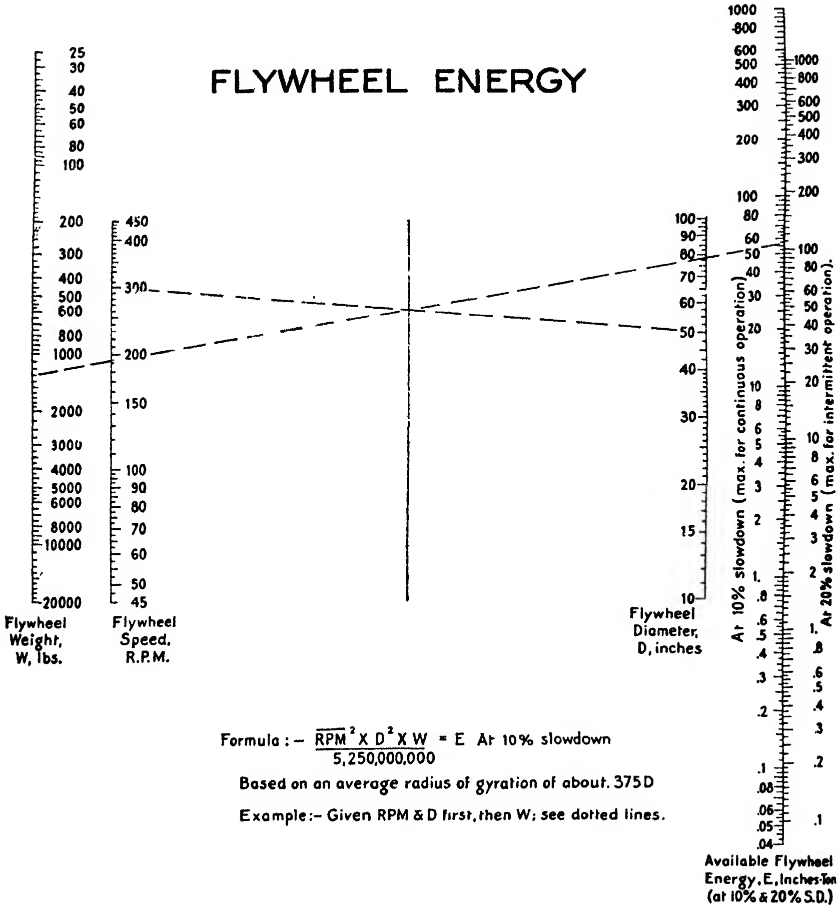


CHART XI

Read the inner scale if the press is to work continuously and the outer scale if it is to be tripped for every stroke.

If the result indicates that the wheel will not furnish the energy required, check whether the motor will handle the deficiency as discussed later, or go to a geared press, or increase the weight or speed of the flywheel.

Operating Velocities.—Chart XII is a simple multiplying nomogram for surface velocities of rotating parts. The formula is:

$$V = \pi \times d = \text{RPM}/12 \tag{45}$$

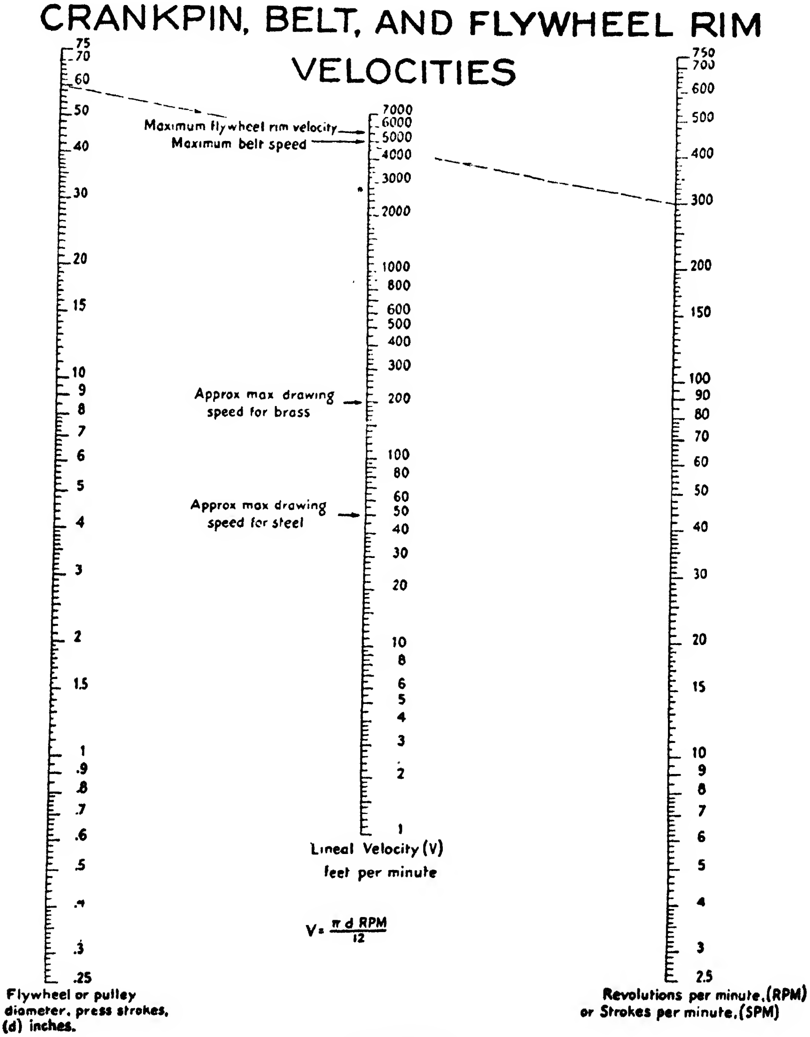


CHART XII

in which velocity V in feet per minute is obtained from the diameter d in inches of a flywheel or pulley or the stroke of a crankshaft and the revolutions or strokes per minute of the wheel or shaft respectively. The chart is read from the outer scales to the center, as indicated by the dotted lines.

For safety with respect to centrifugal forces, cast-iron flywheels should not turn faster than 5500 ft. per min. on their surface. Approaching that speed they should be fairly carefully balanced for the sake of their bearings.

The most economical belt speed is considered to be 5000 ft. per min., though many belts run slower. It is for this reason that large presses, carrying belts too heavy to shift, are belted direct on the flywheel.

The chart may also be used to check drawing speeds (crankpin velocity) for comparative purposes. For drawing steel, the approximate limit of 50 ft. per min. is set by the tendency of the sheet to pick up on the die. The limit of 200 ft. per min. indicated for brass is especially for free-drawing jobs where the dies do not lock the metal at the start.

For figuring the drawing velocity more accurately than by Chart XII, the point in the stroke at which the draw actually begins must be taken into consideration. *Chart XIII* is provided for this purpose. As may be noted in Fig. 177, the difference between the crankpin velocity (Chart XII) and the momentary slide velocity (Chart XIII) is greatest as bottom stroke is approached. Chart XIII is based upon the formula:

$$V = \pi \times d \sin a \times \mathrm{SPM}/12 \tag{46}$$

or

$$V = 0.5233 \times \mathrm{SPM} \times \sqrt{dy - y^2} \tag{35}$$

in which V = maximum drawing velocity, in feet per minute;
d = press stroke, in inches;
SPM = strokes per minute of slide (continuous);
y = distance up from bottom stroke that drawing begins (working stroke), in inches;
a = angle up from bottom stroke at which drawing begins, in degrees. Value a is eliminated in formula 35.

Chart XIII is read by selecting the "working stroke," which is equal to the depth of draw plus an allowance for stripping in the case of push-through work, then traveling horizontally to a junction with the arc for the press stroke, thence vertically to the diagonal for the strokes per minute, thence horizontally to the contact velocity. Thus in making a 4-in.-deep draw in a 20-in. stroke press at 12 SPM, the chart shows the drawing velocity at the start to be 50 ft. per min. which should be satisfactory for steel.

Belt and Motor Energy.—For drawing work on presses driven by a flat belt from a line shaft, or motor, it is possible (below) to approximate the amount of the load which the belt will take care of. It is then possible with Chart XI to check whether there is sufficient flywheel energy to take care of the balance. The following formula for punch pressure P in tons (derived from belt pull) is based upon an assumption of 75-lb. pull per inch of width of double-ply leather belt.

$$P = 0.0375w \times V/v \tag{47}$$

In it, w = belt width in inches;
v = crankpin velocity from Chart XII;
V = belt velocity from the same chart, based upon the diameter and RPM of the flywheel or pulley, whichever is belted.

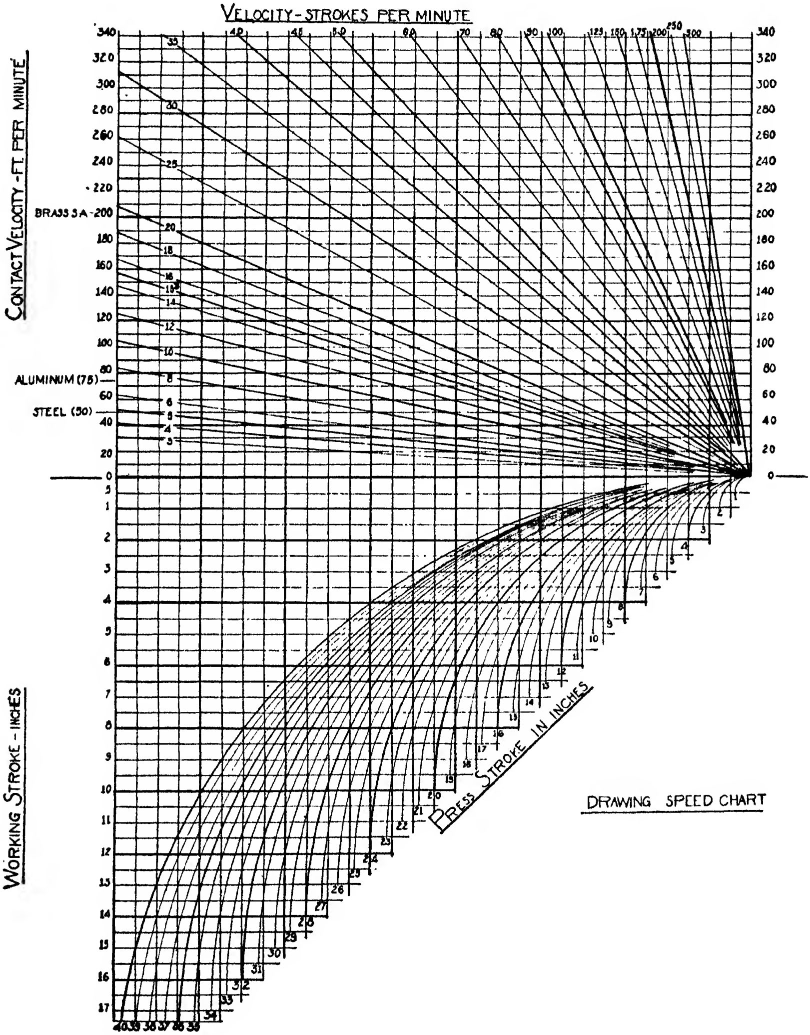


CHART XIII

The value of P obtained may be increased somewhat by multiplying it by the average mechanical advantage of the crank action from Fig. 425. To convert

this to energy in inch-tons, multiply P by the working distance of punch travel in inches.

For a V-belt or geared motor drive the following formula may be used to approximate the energy E (in inch-tons) which the motor will deliver to help the flywheel during the drawing portion of the stroke.

$$E = 0.55 \times \theta \times \mathrm{HP/SPM} \tag{48}$$

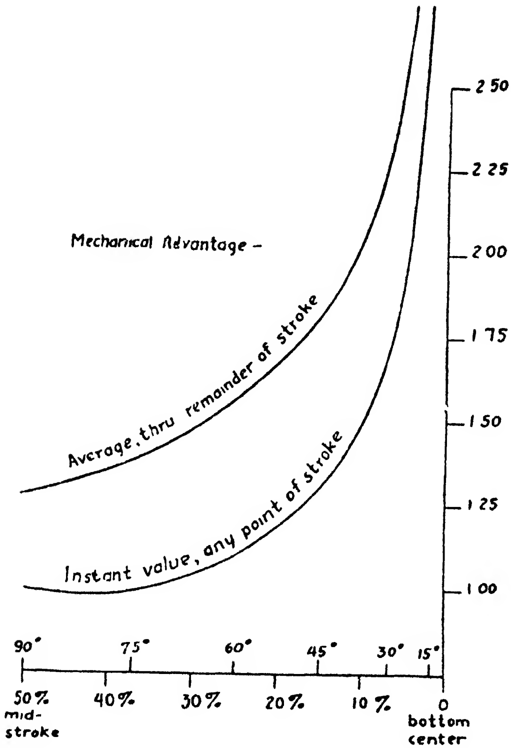


FIG. 425.—The mechanical advantage of belt pull over punch pressure due to crank action.

in which θ (theta) = the number of degrees (not over 90°) that the crankpin travels during the actual drawing portion of the stroke;
HP = the horsepower of the motor without overload allowance;
SPM = the speed of the press in strokes per minute.

Motor Horsepower.—Motor sizes specified for punch presses are usually blanket recommendations to cover the wide range of work which may be put in the average all-purpose press. They are frequently high for blanking or coining operations and low for deep drawing operations.

If the details of the work to be done are known, it is possible to approximate the motor requirements fairly closely. As explained in previous sections, the energy E in inch-tons to do the work is the product of the average working pressure P in tons and the actual working distance l in inches:

$$E = P \times l \times C \qquad (49)$$

To this must be added a liberal percentage, C, to cover machine friction, machine deflection, inertia of gearing in the case of friction clutch presses, spring stripping losses, etc.

If the flywheel alone is capable of delivering the total energy requirement,

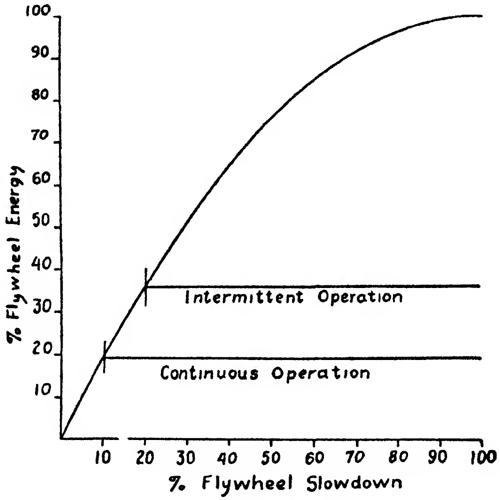


FIG. 426—The relation between slow-down and energy delivered by flywheels.

the motor need only return the wheel to speed, spreading its delivery of power over the whole cycle. Then the motor horsepower should be approximately:

$$\mathrm{HP}_1 = 0.005 \times E \times \mathrm{SPM} \qquad (50)$$

in which the energy, E, required per stroke, in inch-tons, is multiplied by the number of strokes per minute, with a suitable constant to convert inch-tons per minute to horsepower. In the case of intermittent action, take a value between the maximum number of strokes per minute that the operator can make and total rated speed of the press.

In drawing operations which are spread out over an angle θ of, say, 35 to 85° of the cycle, it is possible that a larger motor may be required to take care of the portion of the working load which the flywheel cannot handle, than would be required to return the flywheel to speed, as figured above. Then

HP_1 just obtained should be compared with HP_2 given by the following formula, and the larger value taken.

$$HP_2 = 1.82 \times SPM \times (E_1 - E_2)/\theta \tag{51}$$

In this formula HP_2 = horsepower required during the working period to take care of the flywheel deficiency;

SPM = the press speed (running continuously) in strokes per minute;

$(E_1 - E_2)$ = energy difference in inch-tons between the job requirement E_1 and the flywheel energy available E_2;

θ = the working part of the cycle in degrees.

At the higher press speeds it has frequently been found necessary to select motors with capacities 100 per cent and more in excess of the theoretical horsepower (HP_1), depending upon the type of the motor and its capacity to react to the very rapid pulsations of the energy demand.

Punch press motors must usually be capable of taking repeated slow-downs of 10 to 20 per cent and even more with an overload of, say, 100 per cent. Fig. 426 may be used to check the amount of flywheel slow-down, given the portion of the flywheel energy required.

TABLE XXV

APPROXIMATE DIAMETERS OF BLANKS FOR SHELLS

The approximate blank sizes given on the following pages are figured from the formula:

$$D = \sqrt{d^2 + 4dh}$$

D = dia. of blank. d = dia. of shell.
h = height of shell.

It should be noted that the blank sizes given are approximate only. They do not include any allowance for stretch of metal and are figured without reference to thickness of metal, and are based on using "Bliss" standard die construction. Shells are figured with sharp corners

Diameter of Shell	HEIGHT OF SHELL														Diameter of Shell
	1/2	5/8	3/4	7/8	1	1 1/8	1 1/4	1 3/8	1 1/2	1 5/8	1 3/4	1 7/8	2	2 1/4	
1/4	.75	.83	90	97	1.03	1.09	1.15	1.20	1.25	1.30	1.34	1.39	1.43	1.52	1/4
3/8	94	1.04	1.13	1.21	1.28	1.34	1.42	1.48	1.55	1.61	1.67	1.71	1.78	1.88	3/8
1/2	1.12	1.22	1.32	1.41	1.50	1.58	1.66	1.73	1.80	1.87	1.93	2.00	2.07	2.18	1/2
5/8	1.28	1.40	1.50	1.60	1.70	1.79	1.88	1.96	2.04	2.11	2.19	2.26	2.32	2.46	5/8
3/4	1.44	1.56	1.67	1.78	1.89	1.98	2.08	2.16	2.25	2.33	2.41	2.48	2.56	2.70	3/4
7/8	1.59	1.72	1.84	1.95	2.06	2.16	2.26	2.36	2.45	2.54	2.62	2.70	2.78	2.94	7/8
1	1.73	1.87	2.00	2.12	2.23	2.34	2.45	2.55	2.64	2.74	2.82	2.91	3.00	3.16	1
1 1/8	1.87	2.02	2.15	2.28	2.40	2.51	2.62	2.73	2.83	2.93	3.02	3.11	3.21	3.37	1 1/8
1 1/4	2.01	2.16	2.30	2.43	2.56	2.68	2.80	2.90	3.01	3.11	3.22	3.31	3.40	3.58	1 1/4
1 3/8	2.16	2.31	2.45	2.59	2.72	2.84	2.96	3.08	3.18	3.29	3.39	3.49	3.59	3.77	1 3/8
1 1/2	2.29	2.45	2.60	2.74	2.87	3.00	3.12	3.24	3.36	3.46	3.58	3.67	3.77	3.97	1 1/2
1 5/8	2.42	2.59	2.74	2.89	3.02	3.15	3.28	3.40	3.52	3.63	3.74	3.85	3.95	4.15	1 5/8
1 3/4	2.56	2.72	2.88	3.03	3.17	3.30	3.43	3.56	3.68	3.80	3.91	4.03	4.14	4.34	1 3/4
1 7/8	2.70	2.86	3.02	3.18	3.32	3.46	3.59	3.72	3.84	3.97	4.08	4.20	4.30	4.52	1 7/8
2	2.83	3.00	3.16	3.31	3.46	3.61	3.75	3.87	4.00	4.12	4.24	4.36	4.47	4.69	2
2 1/8	2.96	3.13	3.30	3.46	3.61	3.75	3.89	4.02	4.16	4.28	4.40	4.52	4.64	4.86	2 1/8
2 1/4	3.09	3.27	3.44	3.60	3.75	3.90	4.04	4.18	4.31	4.44	4.56	4.68	4.80	5.03	2 1/4
2 3/8	3.22	3.40	3.57	3.74	3.89	4.04	4.18	4.32	4.46	4.59	4.72	4.84	4.96	5.20	2 3/8
2 1/2	3.35	3.54	3.71	3.87	4.03	4.18	4.33	4.47	4.61	4.74	4.87	5.00	5.12	5.36	2 1/2
2 5/8	3.48	3.67	3.84	4.01	4.17	4.32	4.47	4.62	4.76	4.89	5.03	5.15	5.28	5.52	2 5/8
2 3/4	3.61	3.80	3.98	4.15	4.31	4.47	4.62	4.76	4.90	5.04	5.18	5.31	5.44	5.68	2 3/4
2 7/8	3.75	3.93	4.11	4.28	4.45	4.60	4.76	4.91	5.05	5.19	5.33	5.46	5.59	5.84	2 7/8
3	3.87	4.06	4.24	4.42	4.58	4.74	4.90	5.05	5.20	5.34	5.48	5.61	5.74	6.00	3
3 1/8	4.00	4.19	4.38	4.55	4.72	4.88	5.04	5.19	5.34	5.48	5.63	5.76	5.90	6.16	3 1/8
3 1/4	4.13	4.32	4.51	4.68	4.85	5.02	5.18	5.33	5.48	5.63	5.77	5.91	6.05	6.31	3 1/4
3 3/8	4.26	4.45	4.64	4.82	4.99	5.15	5.31	5.47	5.62	5.77	5.92	6.05	6.19	6.47	3 3/8
3 1/2	4.39	4.58	4.77	4.95	5.12	5.29	5.45	5.61	5.77	5.91	6.06	6.20	6.35	6.61	3 1/2
3 5/8	4.51	4.71	4.90	5.08	5.26	5.43	5.59	5.75	5.90	6.06	6.21	6.35	6.49	6.76	3 5/8

3¾	4.64	4.84	5.03	5.21	5.39	5.56	5.73	5.89	6.04	6.20	6.35	6.49	6.63	6.91	3¾
3⅞	4.77	4.97	5.16	5.34	5.52	5.69	5.86	6.02	6.18	6.34	6.49	6.64	6.78	7.06	3⅞
4	4.90	5.10	5.29	5.48	5.66	5.83	6.00	6.16	6.32	6.48	6.63	6.78	6.92	7.21	4
4⅛	5.02	5.22	5.42	5.61	5.79	5.96	6.13	6.30	6.46	6.62	6.77	6.92	7.07	7.36	4⅛
4¼	5.15	5.35	5.55	5.74	5.92	6.09	6.27	6.43	6.60	6.76	6.91	7.06	7.21	7.50	4¼
4⅜	5.28	5.48	5.68	5.87	6.05	6.23	6.40	6.57	6.73	6.89	7.05	7.21	7.35	7.64	4⅜
4½	5.40	5.61	5.81	6.00	6.18	6.36	6.53	6.70	6.87	7.03	7.19	7.35	7.50	7.79	4½
4⅝	5.53	5.74	5.93	6.13	6.31	6.49	6.67	6.84	7.01	7.17	7.33	7.48	7.64	7.93	4⅝
4¾	5.66	5.86	6.06	6.26	6.44	6.62	6.80	6.97	7.14	7.31	7.47	7.62	7.78	8.08	4¾
4⅞	5.78	5.99	6.19	6.39	6.57	6.76	6.93	7.11	7.28	7.44	7.60	7.76	7.92	8.22	4⅞
5	5.91	6.12	6.32	6.52	6.70	6.89	7.07	7.24	7.41	7.58	7.74	7.90	8.06	8.36	5
5⅛	6.04	6.25	6.45	6.64	6.83	7.02	7.20	7.37	7.55	7.72	7.88	8.04	8.21	8.51	5⅛
5¼	6.17	6.37	6.58	6.77	6.96	7.15	7.33	7.51	7.68	7.85	8.02	8.18	8.34	8.65	5¼
5⅜	6.29	6.50	6.71	6.90	7.09	7.28	7.46	7.64	7.83	7.99	8.15	8.31	8.48	8.79	5⅜
5½	6.42	6.63	6.83	7.03	7.22	7.41	7.60	7.77	7.95	8.12	8.29	8.45	8.61	8.93	5½
5⅝	6.54	6.76	6.96	7.16	7.35	7.54	7.73	7.91	8.08	8.25	8.42	8.59	8.75	9.07	5⅝
5¾	6.67	6.88	7.09	7.29	7.48	7.67	7.86	8.04	8.22	8.39	8.56	8.72	8.89	9.20	5¾
5⅞	6.80	7.01	7.22	7.42	7.61	7.80	7.99	8.17	8.35	8.52	8.69	8.86	9.02	9.34	5⅞
6	6.92	7.14	7.34	7.55	7.74	7.93	8.12	8.30	8.48	8.66	8.83	9.00	9.16	9.48	6
6¼	7.18	7.39	7.60	7.80	8.00	8.19	8.38	8.57	8.75	8.92	9.10	9.27	9.44	9.76	6¼
6½	7.43	7.64	7.85	8.06	8.26	8.45	8.64	8.83	9.01	9.19	9.36	9.54	9.71	10.03	6½
6¾	7.68	7.90	8.11	8.31	8.51	8.71	8.90	9.09	9.27	9.45	9.63	9.80	9.97	10.31	6¾
7	7.93	8.15	8.36	8.57	8.77	8.97	9.16	9.35	9.53	9.72	9.90	10.07	10.24	10.58	7
7¼	8.18	8.40	8.62	8.82	9.03	9.22	9.42	9.61	9.80	9.98	10.16	10.34	10.51	10.85	7¼
7½	8.44	8.66	8.87	9.08	9.28	9.48	9.68	9.87	10.06	10.24	10.42	10.60	10.78	11.12	7½
7¾	8.69	8.91	9.12	9.33	9.54	9.74	9.94	10.13	10.32	10.50	10.69	10.87	11.04	11.39	7¾
8	8.94	9.16	9.38	9.59	9.79	10.00	10.19	10.39	10.58	10.77	10.95	11.13	11.31	11.66	8
8¼	9.19	9.41	9.63	9.84	10.05	10.25	10.45	10.65	10.84	11.03	11.21	11.39	11.57	11.92	8¼
8½	9.44	9.66	9.88	10.10	10.30	10.51	10.71	10.90	11.10	11.29	11.47	11.66	11.84	12.19	8½
8¾	9.69	9.92	10.13	10.35	10.56	10.76	10.96	11.16	11.36	11.55	11.73	11.92	12.10	12.46	8¾
9	9.95	10.17	10.39	10.60	10.81	11.02	11.21	11.42	11.61	11.81	11.99	12.18	12.36	12.72	9
9¼	10.20	10.42	10.64	10.85	11.07	11.27	11.48	11.68	11.87	12.07	12.26	12.44	12.63	12.99	9¼
9½	10.45	10.67	10.89	11.11	11.32	11.53	11.73	11.93	12.13	12.32	12.52	12.70	12.89	13.25	9½
9¾	10.70	10.92	11.14	11.36	11.57	11.78	11.99	12.19	12.39	12.58	12.77	12.96	13.15	13.52	9¾
10	10.95	11.18	11.40	11.61	11.83	12.04	12.24	12.44	12.64	12.84	13.03	13.22	13.41	13.78	10
10¼	11.20	11.43	11.65	11.87	12.08	12.29	12.50	12.70	12.90	13.10	13.29	13.48	13.67	14.04	10¼
10½	11.45	11.68	11.90	12.12	12.33	12.54	12.75	12.96	13.16	13.36	13.55	13.74	13.93	14.30	10½
10¾	11.70	11.93	12.15	12.37	12.59	12.80	13.01	13.21	13.41	13.61	13.81	14.00	14.19	14.56	10¾
11	11.95	12.18	12.40	12.62	12.84	13.05	13.26	13.47	13.67	13.87	14.07	14.26	14.45	14.83	11
11¼	12.20	12.43	12.67	12.91	13.09	13.30	13.52	13.72	13.93	14.13	14.33	14.52	14.71	15.08	11¼
11½	12.45	12.65	12.90	13.11	13.35	13.56	13.77	13.98	14.18	14.38	14.58	14.78	14.97	15.35	11½
11¾	12.66	12.92	13.16	13.39	13.59	13.82	14.03	14.23	14.44	14.63	14.84	15.04	15.22	15.60	11¾
12	12.96	13.20	13.42	13.63	13.86	14.07	14.28	14.49	14.70	14.88	15.10	15.30	15.50	15.88	12

TABLE XXV—*Continued*

APPROXIMATE DIAMETERS OF BLANKS FOR SHELLS

in the bottom. Diameter of shell should be taken from center of thickness of side walls. Sizes of blanks for shells vary according to the varying conditions of die construction; such as fit of die and punch in relation to each other, the size of drawing corner on the die or punch or amount of pressure on blank holding surfaces. The character of metal, whether sheet steel, brass, copper, aluminum, nickel, zinc, silver or gold, and its qualities as regards hardness or softness also have a determining influence.

Diameter of Shell	HEIGHT OF SHELL														Diameter of Shell
	2½	2¾	3	3¼	3½	3¾	4	4¼	4½	4¾	5	5¼	5½	5¾	
¼	1.59	1.67	1.75	1.82	1.89	1.95	2.02	2.08	2.13	2.20	2.25	2.31	2.36	2.41	¼
⅜	1.98	2.07	2.16	2.24	2.32	2.40	2.48	2.55	2.63	2.70	2.76	2.83	2.90	2.96	⅜
½	2.29	2.39	2.50	2.60	2.69	2.78	2.88	2.96	3.04	3.12	3.20	3.28	3.35	3.42	½
⅝	2.58	2.69	2.80	2.92	3.02	3.12	3.23	3.32	3.42	3.50	3.59	3.68	3.76	3.84	⅝
¾	2.84	2.96	3.09	3.21	3.32	3.43	3.54	3.65	3.75	3.85	3.94	4.03	4.13	4.22	¾
⅞	3.08	3.22	3.38	3.50	3.63	3.75	3.84	3.95	4.06	4.17	4.27	4.38	4.47	4.57	⅞
1	3.31	3.46	3.61	3.74	3.87	4.00	4.13	4.24	4.35	4.46	4.58	4.69	4.79	4.89	1
1⅛	3.53	3.69	3.84	3.98	4.12	4.26	4.39	4.51	4.63	4.75	4.87	4.98	5.10	5.21	1⅛
1¼	3.75	3.91	4.07	4.22	4.37	4.51	4.65	4.78	4.90	5.03	5.15	5.27	5.39	5.50	1¼
1⅜	3.95	4.12	4.28	4.44	4.59	4.74	4.88	5.02	5.16	5.29	5.42	5.54	5.67	5.79	1⅜
1½	4.15	4.33	4.50	4.66	4.82	4.97	5.12	5.26	5.40	5.54	5.68	5.81	5.93	6.07	1½
1⅝	4.34	4.53	4.70	4.87	5.03	5.20	5.35	5.50	5.64	5.78	5.92	6.06	6.20	6.33	1⅝
1¾	4.54	4.73	4.90	5.08	5.25	5.42	5.57	5.72	5.88	6.02	6.17	6.31	6.45	6.58	1¾
1⅞	4.71	4.91	5.10	5.28	5.45	5.62	5.79	5.95	6.10	6.25	6.41	6.55	6.69	6.83	1⅞
2	4.90	5.10	5.29	5.48	5.65	5.83	6.00	6.16	6.32	6.48	6.63	6.78	6.93	7.07	2
2⅛	5.08	5.28	5.48	5.67	5.85	6.03	6.21	6.38	6.54	6.70	6.86	7.01	7.16	7.31	2⅛
2¼	5.25	5.46	5.66	5.86	6.05	6.23	6.41	6.58	6.75	6.91	7.08	7.23	7.39	7.54	2¼
2⅜	5.42	5.64	5.84	6.04	6.24	6.42	6.61	6.78	6.96	7.13	7.29	7.45	7.61	7.76	2⅜
2½	5.59	5.81	6.02	6.22	6.42	6.61	6.80	6.98	7.16	7.33	7.50	7.66	7.82	7.98	2½
2⅝	5.76	5.98	6.20	6.40	6.61	6.80	6.99	7.18	7.36	7.53	7.71	7.88	8.04	8.20	2⅝
2¾	5.92	6.15	6.37	6.58	6.79	6.99	7.18	7.37	7.55	7.73	7.91	8.08	8.25	8.41	2¾
2⅞	6.08	6.32	6.54	6.76	6.96	7.17	7.37	7.56	7.75	7.93	8.11	8.29	8.46	8.62	2⅞
3	6.25	6.48	6.71	6.93	7.14	7.35	7.55	7.75	7.94	8.12	8.30	8.48	8.66	8.83	3
3⅛	6.40	6.64	6.87	7.10	7.32	7.52	7.73	7.93	8.12	8.31	8.50	8.68	8.86	9.03	3⅛
3¼	6.56	6.80	7.04	7.26	7.48	7.70	7.91	8.11	8.31	8.50	8.69	8.88	9.06	9.23	3¼
3⅜	6.72	6.96	7.20	7.43	7.66	7.87	8.08	8.29	8.49	8.69	8.88	9.07	9.25	9.43	3⅜
3½	6.87	7.12	7.37	7.60	7.83	8.05	8.26	8.47	8.68	8.87	9.06	9.26	9.45	9.63	3½
3⅝	7.03	7.28	7.52	7.76	7.99	8.21	8.43	8.65	8.85	9.06	9.25	9.45	9.64	9.82	3⅝

3¾	7.18	7.43	7.68	7.92	8.16	8.38	8.60	8.82	9.03	9.23	9.44	9.63	9.82	10.01	3¾
3⅞	7.33	7.59	7.84	8.08	8.32	8.55	8.77	8.99	9.20	9.41	9.61	9.82	10.01	10.20	3⅞
4	7.48	7.74	8.00	8.24	8.48	8.71	8.94	9.16	9.38	9.59	9.79	10.00	10.20	10.39	4
4⅛	7.63	7.89	8.15	8.40	8.64	8.88	9.11	9.33	9.55	9.76	9.97	10.18	10.38	10.57	4⅛
4¼	7.78	8.05	8.31	8.56	8.80	9.04	9.27	9.50	9.72	9.94	10.15	10.35	10.56	10.76	4¼
4⅜	7.93	8.20	8.46	8.71	8.96	9.20	9.44	9.67	9.89	10.11	10.32	10.53	10.74	10.94	4⅜
4½	8.07	8.35	8.61	8.87	9.12	9.36	9.60	9.83	10.06	10.28	10.50	10.71	10.92	11.12	4½
4⅝	8.22	8.50	8.76	9.02	9.28	9.52	9.76	10.00	10.22	10.45	10.67	10.88	11.09	11.30	4⅝
4¾	8.37	8.64	8.91	9.18	9.43	9.68	9.92	10.16	10.39	10.62	10.84	11.05	11.27	11.47	4¾
4⅞	8.51	8.79	9.06	9.33	9.59	9.84	10.08	10.32	10.55	10.78	11.01	11.23	11.44	11.65	4⅞
5	8.66	8.94	9.21	9.48	9.74	10.00	10.24	10.48	10.72	10.95	11.18	11.40	11.61	11.83	5
5⅛	8.80	9.09	9.37	9.63	9.90	10.15	10.40	10.65	10.88	11.12	11.34	11.57	11.79	12.00	5⅛
5¼	8.94	9.23	9.51	9.78	10.05	10.31	10.56	10.80	11.04	11.28	11.51	11.74	11.96	12.17	5¼
5⅜	9.09	9.38	9.66	9.93	10.20	10.46	10.72	10.96	11.20	11.44	11.68	11.90	12.13	12.35	5⅜
5½	9.23	9.52	9.81	10.08	10.35	10.62	10.87	11.12	11.36	11.60	11.84	12.07	12.29	12.52	5½
5⅝	9.37	9.67	9.95	10.23	10.50	10.77	11.02	11.28	11.52	11.76	12.00	12.23	12.46	12.69	5⅝
5¾	9.51	9.81	10.10	10.38	10.65	10.92	11.18	11.43	11.68	11.92	12.16	12.40	12.63	12.85	5¾
5⅞	9.65	9.95	10.24	10.52	10.80	11.07	11.33	11.59	11.84	12.08	12.32	12.56	12.79	13.02	5⅞
6	9.79	10.09	10.39	10.67	10.95	11.22	11.48	11.74	12.00	12.24	12.48	12.72	12.96	13.19	6
6¼	10.07	10.38	10.68	10.96	11.25	11.52	11.79	12.05	12.31	12.56	12.80	13.05	13.28	13.52	6¼
6½	10.35	10.66	10.96	11.25	11.54	11.82	12.09	12.36	12.62	12.87	13.12	13.37	13.61	13.85	6½
6¾	10.63	10.94	11.25	11.54	11.83	12.11	12.39	12.66	12.92	13.18	13.43	13.68	13.93	14.17	6¾
7	10.90	11.22	11.53	11.83	12.12	12.40	12.68	12.96	13.23	13.49	13.74	14.00	14.24	14.49	7
7¼	11.18	11.50	11.81	12.11	12.41	12.70	12.98	13.25	13.52	13.79	14.05	14.31	14.56	14.80	7¼
7½	11.45	11.77	12.09	12.39	12.69	12.99	13.27	13.55	13.82	14.09	14.36	14.62	14.87	15.12	7½
7¾	11.72	12.05	12.37	12.68	12.98	13.27	13.56	13.84	14.12	14.39	14.66	14.92	15.18	15.43	7¾
8	11.99	12.32	12.64	12.96	13.26	13.56	13.85	14.14	14.42	14.69	14.96	15.23	15.49	15.74	8
8¼	12.27	12.60	12.92	13.23	13.54	13.84	14.14	14.43	14.71	14.99	15.26	15.53	15.79	16.05	8¼
8½	12.53	12.87	13.20	13.51	13.82	14.13	14.43	14.72	15.00	15.28	15.56	15.83	16.10	16.36	8½
8¾	12.80	13.14	13.47	13.79	14.10	14.41	14.71	15.00	15.29	15.58	15.86	16.13	16.40	16.66	8¾
9	13.07	13.41	13.74	14.07	14.38	14.69	14.99	15.29	15.58	15.87	16.15	16.43	16.70	16.97	9
9¼	13.34	13.68	14.02	14.34	14.66	14.97	15.28	15.58	15.87	16.16	16.44	16.72	17.00	17.26	9¼
9½	13.61	13.95	14.29	14.61	14.94	15.25	15.56	15.86	16.16	16.45	16.74	17.02	17.29	17.57	9½
9¾	13.87	14.22	14.56	14.89	15.21	15.53	15.84	16.14	16.44	16.74	17.03	17.31	17.59	17.86	9¾
10	14.14	14.49	14.83	15.16	15.49	15.81	16.12	16.43	16.73	17.02	17.31	17.60	17.88	18.15	10
10¼	14.40	14.75	15.10	15.43	15.76	16.08	16.40	16.71	17.01	17.31	17.60	17.89	18.18	18.46	10¼
10½	14.66	15.02	15.36	15.70	16.03	16.36	16.68	16.99	17.29	17.59	17.89	18.18	18.47	18.75	10½
10¾	14.93	15.29	15.63	15.97	16.31	16.63	16.95	17.27	17.58	17.88	18.18	18.47	18.76	19.04	10¾
11	15.19	15.55	15.90	16.24	16.58	16.91	17.23	17.55	17.86	18.16	18.46	18.76	19.05	19.33	11
11¼	15.46	15.82	16.17	16.52	16.84	17.17	17.50	17.81	18.12	18.44	18.74	19.03	19.33	19.62	11¼
11½	15.72	16.08	16.43	16.78	17.11	17.45	17.78	18.09	18.41	18.71	19.02	19.32	19.63	19.92	11½
11¾	15.98	16.34	16.70	17.05	17.39	17.73	18.05	18.38	18.70	19.01	19.32	19.61	19.90	20.21	11¾
12	16.24	16.61	16.96	17.32	17.66	18.00	18.33	18.64	18.97	19.28	19.59	19.89	20.20	20.49	12

Table XXV—*Continued*

APPROXIMATE DIAMETERS OF BLANKS FOR SHELLS

Diameter of Shell	HEIGHT OF SHELL 6	6½	7	7½	8	8½	9	9½	10	10½	11	11½	12	Diameter of Shell
¼	2.46	2.56	2.66	2.75	2.83	2.93	3.01	3.09	3.17	3.25	3.33	3.40	3.48	¼
⅜	3.03	3.15	3.27	3.38	3.48	3.59	3.70	3.80	3.90	3.98	4.08	4.17	4.26	⅜
½	3.50	3.64	3.77	3.90	4.03	4.15	4.27	4.39	4.50	4.61	4.71	4.82	4.93	½
⅝	3.92	4.08	4.23	4.38	4.52	4.65	4.78	4.91	5.04	5.16	5.28	5.39	5.51	⅝
¾	4.30	4.48	4.64	4.80	4.96	5.10	5.25	5.39	5.53	5.66	5.79	5.92	6.05	¾
⅞	4.66	4.84	5.03	5.19	5.36	5.52	5.68	5.83	5.98	6.12	6.26	6.40	6.53	⅞
1	5.00	5.19	5.39	5.57	5.74	5.92	6.08	6.24	6.40	6.56	6.71	6.86	7.00	1
1⅛	5.31	5.52	5.72	5.92	6.10	6.28	6.46	6.63	6.80	6.96	7.12	7.28	7.43	1⅛
1¼	5.61	5.84	6.04	6.25	6.45	6.64	6.82	7.00	7.18	7.35	7.52	7.68	7.84	1¼
1⅜	5.90	6.13	6.35	6.57	6.78	6.97	7.16	7.35	7.54	7.73	7.89	8.07	8.24	1⅜
1½	6.19	6.42	6.65	6.87	7.09	7.30	7.50	7.70	7.89	8.08	8.26	8.44	8.62	1½
1⅝	6.45	6.70	6.94	7.17	7.39	7.61	7.82	8.02	8.22	8.42	8.61	8.80	8.98	1⅝
1¾	6.71	6.97	7.22	7.46	7.69	7.91	8.13	8.34	8.55	8.75	8.95	9.14	9.33	1¾
1⅞	6.96	7.23	7.49	7.73	7.97	8.20	8.43	8.64	8.86	9.07	9.27	9.48	9.67	1⅞
2	7.21	7.49	7.75	8.00	8.25	8.48	8.72	8.94	9.17	9.38	9.59	9.80	10.00	2
2⅛	7.45	7.73	8.00	8.26	8.52	8.76	9.00	9.23	9.46	9.68	9.90	10.11	10.32	2⅛
2¼	7.68	7.97	8.25	8.52	8.78	9.03	9.28	9.52	9.75	9.98	10.21	10.42	10.63	2¼
2⅜	7.91	8.21	8.49	8.77	9.03	9.29	9.55	9.79	10.03	10.26	10.49	10.72	10.94	2⅜
2½	8.14	8.44	8.73	9.01	9.29	9.55	9.81	10.06	10.31	10.55	10.78	11.01	11.24	2½
2⅝	8.36	8.67	8.97	9.25	9.53	9.80	10.07	10.33	10.58	10.82	11.06	11.30	11.53	2⅝
2¾	8.58	8.89	9.20	9.49	9.78	10.05	10.32	10.59	10.84	11.09	11.33	11.58	11.81	2¾
2⅞	8.79	9.11	9.42	9.72	10.01	10.29	10.57	10.84	11.11	11.35	11.61	11.85	12.09	2⅞
3	9.00	9.33	9.64	9.95	10.25	10.53	10.82	11.09	11.36	11.62	11.87	12.12	12.37	3
3⅛	9.20	9.54	9.86	10.17	10.48	10.77	11.06	11.34	11.61	11.88	12.13	12.39	12.64	3⅛
3¼	9.41	9.75	10.08	10.40	10.70	11.00	11.29	11.58	11.86	12.13	12.39	12.65	12.90	3¼
3⅜	9.61	9.96	10.29	10.61	10.93	11.23	11.53	11.82	12.10	12.37	12.64	12.91	13.17	3⅜
3½	9.81	10.16	10.50	10.83	11.15	11.46	11.76	12.05	12.34	12.62	12.89	13.16	13.43	3½
3⅝	10.00	10.36	10.71	11.04	11.36	11.68	11.98	12.28	12.57	12.86	13.14	13.41	13.68	3⅝

3¾	10.20	10.56	10.91	11.25	11.58	11.90	12.21	12.51	12.80	13.09	13.37	13.65	13.93	3¾
3⅞	10.39	10.76	11.11	11.45	11.79	12.11	12.43	12.74	13.04	13.33	13.62	13.90	14.18	3⅞
4	10.58	10.95	11.31	11.66	12.00	12.33	12.65	12.96	13.26	13.56	13.85	14.14	14.42	4
4⅛	10.76	11.14	11.51	11.86	12.20	12.54	12.86	13.18	13.49	13.79	14.09	14.38	14.66	4⅛
4¼	10.95	11.33	11.71	12.06	12.41	12.75	13.07	13.40	13.72	14.02	14.32	14.61	14.90	4¼
4⅜	11.14	11.52	11.90	12.26	12.61	12.95	13.29	13.61	13.93	14.24	14.54	14.84	15.13	4⅜
4½	11.32	11.71	12.09	12.45	12.81	13.16	13.50	13.82	14.15	14.45	14.77	15.07	15.37	4½
4⅝	11.50	11.90	12.28	12.65	13.01	13.36	13.70	14.04	14.36	14.68	14.99	15.30	15.60	4⅝
4¾	11.68	12.08	12.47	12.84	13.21	13.56	13.91	14.25	14.57	14.90	15.22	15.52	15.83	4¾
4⅞	11.86	12.26	12.65	13.03	13.41	13.76	14.11	14.45	14.79	15.11	15.43	15.74	16.05	4⅞
5	12.04	12.45	12.84	13.23	13.60	13.96	14.32	14.66	15.00	15.33	15.65	15.97	16.28	5
5⅛	12.21	12.63	13.03	13.41	13.79	14.16	14.52	14.86	15.21	15.54	15.87	16.19	16.50	5⅛
5¼	12.39	12.81	13.21	13.60	13.98	14.35	14.71	15.07	15.41	15.75	16.08	16.40	16.72	5¼
5⅜	12.56	12.98	13.39	13.79	14.17	14.54	14.91	15.27	15.61	15.95	16.29	16.61	16.93	5⅜
5½	12.73	13.16	13.57	13.97	14.36	14.73	15.11	15.47	15.82	16.16	16.50	16.83	17.15	5½
5⅝	12.90	13.33	13.75	14.15	14.54	14.93	15.30	15.66	16.02	16.36	16.70	17.04	17.36	5⅝
5¾	13.07	13.51	13.93	14.33	14.73	15.11	15.49	15.86	16.21	16.57	16.91	17.25	17.58	5¾
5⅞	13.24	13.68	14.10	14.51	14.91	15.30	15.68	16.05	16.42	16.77	17.11	17.45	17.79	5⅞
6	13.41	13.85	14.28	14.69	15.10	15.49	15.87	16.24	16.61	16.97	17.32	17.66	18.00	6
6¼	13.74	14.19	14.63	15.05	15.46	15.86	16.25	16.63	17.00	17.36	17.72	18.07	18.41	6¼
6½	14.08	14.53	14.97	15.40	15.82	16.22	16.62	17.00	17.38	17.75	18.11	18.47	18.82	6½
6¾	14.40	14.86	15.31	15.75	16.17	16.58	16.98	17.38	17.76	18.14	18.50	18.87	19.22	6¾
7	14.73	15.19	15.65	16.09	16.52	16.94	17.34	17.74	18.13	18.52	18.89	19.26	19.62	7
7¼	15.05	15.52	15.98	16.43	16.86	17.29	17.70	18.11	18.51	18.89	19.27	19.64	20.01	7¼
7½	15.37	15.85	16.31	16.77	17.21	17.64	18.06	18.47	18.87	19.26	19.65	20.03	20.40	7½
7¾	15.68	16.17	16.64	17.10	17.55	17.98	18.41	18.82	19.23	19.63	20.02	20.40	20.78	7¾
8	15.99	16.49	16.97	17.43	17.88	18.33	18.76	19.18	19.59	19.99	20.39	20.78	21.16	8
8¼	16.31	16.80	17.29	17.76	18.22	18.66	19.10	19.53	19.95	20.36	20.76	21.15	21.54	8¼
8½	16.62	17.12	17.61	18.09	18.55	19.00	19.44	19.88	20.30	20.71	21.11	21.51	21.91	8½
8¾	16.92	17.43	17.93	18.41	18.88	19.34	19.78	20.22	20.65	21.07	21.48	21.88	22.28	8¾
9	17.23	17.74	18.24	18.73	19.20	19.67	20.12	20.56	21.00	21.42	21.84	22.24	22.64	9
9¼	17.53	18.05	18.56	19.05	19.53	20.00	20.45	20.90	21.34	21.77	22.19	22.60	23.00	9¼
9½	17.83	18.36	18.87	19.37	19.85	20.32	20.79	21.24	21.68	22.11	22.54	22.96	23.37	9½
9¾	18.14	18.66	19.18	19.68	20.17	20.65	21.12	21.57	22.02	22.46	22.89	23.31	23.72	9¾
10	18.43	18.97	19.49	20.00	20.49	20.97	21.44	21.90	22.36	22.80	23.24	23.66	24.08	10
10¼	18.73	19.27	19.80	20.31	20.81	21.29	21.77	22.23	22.69	23.14	23.58	24.01	24.43	10¼
10½	19.03	19.57	20.10	20.62	21.12	21.61	22.09	22.56	23.02	23.47	23.92	24.35	24.78	10½
10¾	19.32	19.87	20.40	20.93	21.43	21.93	22.41	22.89	23.35	23.81	24.25	24.69	25.13	10¾
11	19.62	20.17	20.71	21.23	21.74	22.24	22.73	23.21	23.68	24.14	24.59	25.04	25.47	11
11¼	19.90	20.46	21.01	21.54	22.05	22.55	23.06	23.54	24.00	24.47	24.92	25.37	25.82	11¼
11½	20.20	20.76	21.30	21.84	22.36	22.87	23.36	23.85	24.33	24.80	25.25	25.70	26.15	11½
11¾	20.50	21.05	21.61	22.14	22.67	23.18	23.68	24.17	24.66	25.13	25.58	26.04	26.49	11¾
12	20.77	21.35	21.90	22.45	22.97	23.50	23.99	24.48	24.97	25.45	25.93	26.37	26.84	12

TABLE XXVI

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
1/32	0.00077	0.098175	2 9/16	5.1572	8.05033
3/64	0.00173	0.147262	5/8	5.4119	8.24668
1/16	0.00307	0.196350	11/16	5.6727	8.44303
3/32	0.00690	0.294524	3/4	5.9396	8.63938
1/8	0.01227	0.392699	13/16	6.2126	8.83573
5/32	0.01917	0.490874	7/8	6.4918	9.03208
3/16	0 02761	0 589049	15/16	6.7771	9.22843
7/32	0.03758	0.687223	3	7.0686	9.42478
1/4	0.04909	0.785398	1/16	7.3662	9.62113
9/32	0.06213	0.883573	1/8	7.6699	9.81748
5/16	0.07670	0.981748	3/16	7.9798	10.0138
11/32	0.09281	1.07992	1/4	8.2958	10.2102
3/8	0.11045	1.17810	5/16	8.6179	10.4065
13/32	0.12962	1.27627	3/8	8.9462	10.6029
7/16	0.15033	1.37445	7/16	9 2806	10.7992
15/32	0.17257	1.47262	1/2	9.6211	10.9956
1/2	0.19635	1.57080	9/16	9.9678	11.1919
17/32	0.22166	1.66897	5/8	10.321	11.3883
9/16	0.24850	1.76715	11/16	10.680	11.5846
19/32	0.27688	1.86532	3/4	11.045	11.7810
5/8	0.30680	1.96350	13/16	11.416	11.9773
21/32	0.33824	2.06167	7/8	11.793	12.1737
11/16	0.37122	2.15984	15/16	12.177	12.3700
23/32	0.40574	2.25802	4	12.566	12.5664
3/4	0.44179	2.35619	1/16	12 962	12.7627
25/32	0.47937	2.45437	1/8	13.364	12.9591
13/16	0.51849	2.55254	3/16	13.772	13.1554
27/32	0.55914	2.65072	1/4	14 186	13.3518
7/8	0 60132	2.74889	5/16	14.607	13.5481
29/32	0 64504	2.84707	3/8	15 033	13.7445
15/16	0.69029	2.94524	7/16	15.466	13.9408
31/32	0.73708	3.04342	1/2	15.904	14.1372
1	0.78540	3.14159	9/16	16.349	14.3335
1/16	0.88664	3.33794	5/8	16.800	14.5299
1/8	0.99402	3.53429	11/16	17.257	14.7262
3/16	1.1075	3.73064	3/4	17.721	14.9226
1/4	1.2272	3.92699	13/16	18.190	15.1189
5/16	1.3530	4.12334	7/8	18.665	15.3153
3/8	1.4849	4.31969	15/16	19.147	15.5116
7/16	1.6230	4.51604	5	19.635	15.7080
1/2	1.7671	4.71239	1/16	20.129	15.9043
9/16	1.9175	4.90874	1/8	20.629	16.1007
5/8	2.0739	5.10509	3/16	21.135	16.2970
11/16	2.2365	5.30144	1/4	21.648	16.4934
3/4	2.4053	5.49779	5/16	22.166	16.6897
13/16	2.5802	5.69414	3/8	22.691	16.8861
7/8	2.7612	5.89049	7/16	23.221	17.0824
15/16	2.9483	6.08684	1/2	23.758	17.2788
2	3.1416	6.28319	9/16	24.301	17.4751
1/16	3.3410	6.47953	5/8	24.850	17.6715
1/8	3.5466	6.67588	11/16	25.406	17.8678
3/16	3.7583	6.87223	3/4	25.967	18.0642
1/4	3.9761	7.06858	13/16	26.535	18.2605
5/16	4.2000	7.26493	7/8	27.109	18.4569
3/8	4.4301	7.46128	15/16	27.688	18.6532
7/16	4.6664	7.65763	6	28.274	18.8496
1/2	4.9087	7.85398	1/8	29.465	19.2423

Table XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
6¼	30.680	19.6350	13⅜	140.50	42.0188
⅜	31.919	20.0277	½	143.14	42.4115
½	33.183	20.4204	⅝	145.80	42.8042
⅝	34.472	20.8131	¾	148.49	43.1969
¾	35.785	21.2058	⅞	151.20	43.5896
⅞	37.122	21.5984	14	153.94	43.9823
7	38.485	21.9911	⅛	156.70	44.3750
⅛	39.871	22.3838	¼	159.48	44.7677
¼	41.282	22.7765	⅜	162.30	45.1604
⅜	42.718	23.1692	½	165.13	45.5531
½	44.179	23.5619	⅝	167.99	45.9458
⅝	45.664	23.9546	¾	170.87	46.3385
¾	47.173	24.3473	⅞	173.78	46.7312
⅞	48.707	24.7400	15	176.71	47.1239
8	50.265	25.1327	⅛	179.67	47.5166
⅛	51.849	25.5255	¼	182.65	47.9093
¼	53.456	25.9181	⅜	185.66	48.3020
⅜	55.088	26.3108	½	188.69	48.6947
½	56.745	26.7035	⅝	191.75	49.0874
⅝	58.426	27.0962	¾	194.83	49.4801
¾	60.132	27.4889	⅞	197.93	49.8728
⅞	61.862	27.8816	16	201.06	50.2655
9	63.617	28.2743	⅛	204.22	50.6582
⅛	65.397	28.6670	¼	207.39	51.0509
¼	67.201	29.0597	⅜	210.60	51.4436
⅜	69.029	29.4524	½	213.82	51.8363
½	70.882	29.8451	⅝	217.08	52.2290
⅝	72.760	30.2378	¾	220.35	52.6217
¾	74.662	30.6305	⅞	223.65	53.0144
⅞	76.589	31.0232	17	226.98	53.4071
10	78.540	31.4159	⅛	230.33	53.7998
⅛	80.516	31.8086	¼	233.71	54.1925
¼	82.516	32.2013	⅜	237.10	54.5852
⅜	84.541	32.5940	½	240.53	54.9779
½	86.590	32.9867	⅝	243.98	55.3706
⅝	88.664	33.3794	¾	247.45	55.7633
¾	90.763	22.7721	⅞	250.95	56.1560
⅞	92.886	34.1648	18	254.47	56.5487
11	95.033	34.5575	⅛	258.02	56.9414
⅛	97.205	34.9502	¼	261.59	57.3341
¼	99.402	35.3429	⅜	265.18	57.7268
⅜	101.62	35.7356	½	268.80	58.1195
½	103.87	36.1283	⅝	272.45	58.5122
⅝	106.14	36.5210	¾	276.12	58.9049
¾	108.43	36.9137	⅞	279.81	59.2976
⅞	110.75	37.3064	19	283.53	59.6903
12	113.10	37.6991	⅛	287.27	60.0830
⅛	115.47	38.0918	¼	291.04	60.4757
¼	117.86	38.4845	⅜	294.83	60.8684
⅜	120.28	38.8772	½	298.65	61.2611
½	122.72	39.2699	⅝	302.49	61.6538
⅝	125.19	39.6626	¾	306.35	62.0465
¾	127.68	40.0553	⅞	310.24	62.4392
⅞	130.19	40.4480	20	314.16	62.8319
13	132.73	40.8407	⅛	318.10	63.2246
⅛	135.30	41.2334	¼	322.06	63.6173
¼	137.89	41.6261	⅜	326.05	64.0100

TABLE XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
20½	330.06	64.4026	27⅝	599.37	86.7865
⅝	334.10	64.7953	¾	604.81	87.1792
¾	338.16	65.1880	⅞	610.27	87.5719
⅞	342.25	65.5807	28	615.75	87.9646
21	346.36	65.9734	⅛	621.26	88.3573
⅛	350.50	66.3661	¼	626.80	88.7500
¼	354.66	66.7588	⅜	632.36	89.1427
⅜	358.84	67.1515	½	637.94	89.5354
½	363.05	67.5442	⅝	643.55	89.9281
⅝	367.28	67.9369	¾	649.18	90.3208
¾	371.54	68.3296	⅞	656.84	90.7135
⅞	375.83	68.7223	29	660.52	91.1062
22	380.13	69.1150	⅛	666.23	91.4989
⅛	384.46	69.5077	¼	671.96	91.8916
¼	388.82	69.9004	⅜	677.71	92.2843
⅜	393.20	70.2931	½	683.49	92.6770
½	397.61	70.6858	⅝	689.30	93.0697
⅝	402.04	71.0785	¾	695.13	93.4624
¾	406.49	71.4712	⅞	700.98	93.8551
⅞	410.97	71.8639	30	706.86	94.2478
23	415.48	72.2566	⅛	712.76	94.6405
⅛	420.00	72.6493	¼	718.69	95.0332
¼	424.56	73.0420	⅜	724.64	95.4259
⅜	429.13	73.4347	½	730.62	95.8186
½	433.74	73.8274	⅝	736.62	96.2113
⅝	438.36	74.2201	¾	742.64	96.6040
¾	443.01	74.6128	⅞	748.69	96.9967
⅞	447.69	75.0055	31	754.77	97.3894
24	452.39	75.3982	⅛	760.87	97.7821
⅛	457.11	75.7909	¼	766.99	98.1748
¼	461.86	76.1836	⅜	773.14	98.5675
⅜	466.64	76.5765	½	779.31	98.9602
½	471.44	76.9690	⅝	785.51	99.3529
⅝	476.26	77.3617	¾	791.73	99.7456
¾	481.11	77.7544	⅞	797.98	100.138
⅞	485.98	78.1471	32	804.25	100.531
25	490.87	78.5398	⅛	810.54	100.924
⅛	495.79	78.9325	¼	816.86	101.316
¼	500.74	79.3252	⅜	823.21	101.709
⅜	505.71	79.7179	½	829.58	102.102
½	510.71	80.1105	⅝	835.97	102.494
⅝	515.72	80.5033	¾	842.39	102.887
¾	520.77	80.8960	⅞	848.83	103.280
⅞	525.84	81.2887	33	855.30	103.673
26	530.93	81.6814	⅛	861.79	104.065
⅛	536.05	82.0741	¼	868.31	104.458
¼	541.19	82.4668	⅜	874.85	104.851
⅜	546.35	82.8595	½	881.41	105.243
½	551.55	83.2522	⅝	888.00	105.636
⅝	556.76	83.6449	¾	894.62	106.029
¾	562.00	84.0376	⅞	901.26	106.421
⅞	567.27	84.4303	34	907.92	106.814
27	572.56	84.8230	⅛	914.61	107.207
⅛	577.87	85.2157	¼	921.32	107.600
¼	583.21	85.6084	⅜	928.06	107.992
⅜	588.57	86.0011	½	934.82	108.385
½	593.96	86.3938	⅝	941.61	108.788

Table XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
34¾	948.42	109.170	41⅞	1377.2	131.554
⅞	955.25	109.563	42	1385.4	131.947
35	962.11	109.956	⅛	1393.7	132.340
⅛	969.00	110.348	¼	1402.0	132.732
¼	975.91	110.741	⅜	1410.3	133.125
⅜	982.84	111.134	½	1418.6	133.518
½	989.80	111.527	⅝	1427.0	133.910
⅝	996.78	111.919	¾	1435.4	134.303
¾	1003.8	112.312	⅞	1443.8	134.696
⅞	1010.8	112.705	43	1452.2	135.088
36	1017.9	113.097	⅛	1460.7	135.481
⅛	1025.0	113.490	¼	1469.1	135.874
¼	1032.1	113.883	⅜	1477.6	136.267
⅜	1039.2	114.275	½	1486.2	136.659
½	1046.3	114.668	⅝	1494.7	137.052
⅝	1053.5	115.061	¾	1503.3	137.445
¾	1060.7	115.454	⅞	1511.9	137.837
⅞	1068.0	115.846	44	1520.5	138.230
37	1075.2	116.239	⅛	1529.2	138.623
⅛	1082.5	116.632	¼	1537.9	139.015
¼	1089.8	117.024	⅜	1546.6	139.408
⅜	1097.1	117.417	½	1555.3	139.801
½	1104.5	117.810	⅝	1564.0	140.194
⅝	1111.8	118.202	¾	1572.8	140.586
¾	1119.2	118.596	⅞	1581.6	140.979
⅞	1126.7	118.988	45	1590.4	141.372
38	1134.1	119.381	⅛	1599.3	141.764
⅛	1141.6	119.773	¼	1608.2	142.157
¼	1149.1	120.166	⅜	1617.0	142.550
⅜	1156.6	120.559	½	1626.0	142.942
½	1164.2	120.951	⅝	1634.9	143.335
⅝	1171.7	121.344	¾	1643.9	143.728
¾	1179.3	121.737	⅞	1652.9	144.121
⅞	1186.9	122.129	46	1661.9	144.513
39	1194.6	122.522	⅛	1670.9	144.906
⅛	1202.3	122.915	¼	1680.0	145.299
¼	1210.0	123.308	⅜	1689.1	145.691
⅜	1217.7	123.700	½	1698.2	146.084
½	1225.4	124.093	⅝	1707.4	146.477
⅝	1233.2	124.486	¾	1716.5	146.869
¾	1241.0	124.878	⅞	1725.7	147.262
⅞	1248.8	125.271	47	1734.9	147.655
40	1256.6	125.664	⅛	1744.2	148.048
⅛	1264.5	126.056	¼	1753.5	148.440
¼	1272.4	126.449	⅜	1762.7	148.833
⅜	1280.3	126.842	½	1772.1	149.226
½	1288.2	127.235	⅝	1781.4	149.618
⅝	1296.2	127.627	¾	1790.8	150.011
¾	1304.2	128.020	⅞	1800.1	150.404
⅞	1312.2	128.413	48	1809.6	150.796
41	1320.3	128.805	⅛	1819.0	151.189
⅛	1328.3	129.198	¼	1828.5	151.582
¼	1336.4	129.591	⅜	1837.9	151.975
⅜	1344.5	129.993	½	1847.5	152.367
½	1352.7	130.376	⅝	1857.0	152.760
⅝	1360.8	130.769	¾	1866.5	153.153
¾	1369.0	131.161	⅞	1876.1	153.544

Table XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
49	1885.7	153.938	56⅛	2474.0	176.322
⅛	1895.4	154.331	¼	2485.0	176.715
¼	1905.0	154.723	⅜	2496.1	177.107
⅜	1914.7	155.116	½	2507.2	177.500
½	1924.2	155.509	⅝	2518.3	177.893
⅝	1934.2	155.904	¾	2529.4	178.285
¾	1943.9	156.294	⅞	2540.6	178.678
⅞	1953.7	156.687	57	2551.8	179.071
50	1963.5	157.080	⅛	2563.0	179.463
⅛	1973.3	157.472	¼	2574.2	179.856
¼	1983.2	157.865	⅜	2585.4	180.249
⅜	1993.1	158.258	½	2596.7	180.642
½	2003.0	158.650	⅝	2608.0	181.034
⅝	2012.9	159.043	¾	2619 4	181.427
¾	2022.8	159.436	⅞	2630.7	181.820
⅞	2032.8	159.829	58	2642.1	182.212
51	2042.8	160.221	⅛	2653.5	182.605
⅛	2052.8	160.614	¼	2664.9	182.998
¼	2062.9	161.007	⅜	2676.4	183.390
⅜	2073.0	161.399	½	2687.8	183.783
½	2083.1	161.792	⅝	2699.3	184.176
⅝	2093.2	162.185	¾	2710.9	184.569
¾	2103.3	162.577	⅞	2722.4	184.961
⅞	2113.5	162.970	59	2734.0	185.354
52	2123.7	163.363	⅛	2745.6	185.747
⅛	2133.9	163.756	¼	2757.2	186.139
¼	2144.2	164.148	⅜	2768.8	186.532
⅜	2154.5	164.541	½	2780.5	186.925
½	2164.8	164.934	⅝	2792.2	187.317
⅝	2175.1	165.326	¾	2803.9	187.710
¾	2185.4	165.719	⅞	2815.7	188.103
⅞	2195.8	166.112	60	2827.4	188.496
53	2206.2	166.504	⅛	2839.2	188.888
⅛	2216.6	166.897	¼	2851.0	189.281
¼	2227.0	167.290	⅜	2862.9	189.674
⅜	2237.5	167.683	½	2874.8	190.066
½	2248.0	168.075	⅝	2886.6	190.459
⅝	2258.5	168.468	¾	2898.6	190.852
¾	2269.1	168.861	⅞	2910.5	191.244
⅞	2279.6	169.253	61	2922.5	191.637
54	2209.2	169.646	⅛	2934.5	192.030
⅛	2300.8	170.039	¼	2946.5	192.423
¼	2311.5	170.431	⅜	2958.5	192.815
⅜	2322.1	170.824	½	2970.6	193.208
½	2332.8	171.217	⅝	2982.7	193.601
⅝	2343.5	171.609	¾	2994.8	193.993
¾	2354.3	172.002	⅞	3006.9	194.386
⅞	2365.0	172.395	62	3019.1	194.779
55	2375.8	172.788	⅛	3031.3	195.171
⅛	2386.6	173.180	¼	3043.5	195.564
¼	2397.5	173.573	⅜	3055.7	195.957
⅜	2408.3	173.966	½	3068.0	196.350
½	2419.2	174.358	⅝	3080.3	196.742
⅝	2430.1	174.751	¾	3092.6	197.135
¾	2441.1	175.144	⅞	3104.9	197.528
⅞	2452.0	175.536	63	3117.2	197.920
56	2463.0	175.929	⅛	3129.6	198.313

TABLE XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
63¼	3142.0	198.706	70⅜	3889.8	221.090
⅜	3154.5	199.098	½	3903 6	221.482
½	3166.9	199.491	⅝	3917.5	221.875
⅝	3179.4	199.884	¾	3931.4	222.268
¾	3191.9	200.277	⅞	3945.3	222.660
⅞	3204.4	200.669	71	3959.2	223.053
64	3217.0	201.062	⅛	3973.1	223.446
⅛	3229.6	201.455	¼	3987.1	223.838
¼	3242.2	201.847	⅜	4001.1	224.231
⅜	3254.8	202.240	½	4015.2	224.624
½	3267.5	202.633	⅝	4029.2	225.017
⅝	3280.1	203.025	¾	4043.3	225.409
¾	3292.8	203 418	⅞	4057.4	225.802
⅞	3305.6	203.811	72	4071.5	226.195
65	3318.3	204.204	⅛	4085.7	226.587
⅛	3331 1	204.596	¼	4099.8	226.930
¼	3343 9	204.989	⅜	4114.0	227.373
⅜	3356 7	205.382	½	4128.2	227.765
½	3369.6	205.774	⅝	4142.5	228.158
⅝	3382.4	206.167	¾	4156.8	228.551
¾	3395 3	206.560	⅞	4171.1	228.944
⅞	3408.2	206.952	73	4185.4	229.336
66	3421.2	207.345	⅛	4199.7	229.729
⅛	3434.3	207.738	¼	4214.1	230.122
¼	3447.2	208.131	⅜	4228.5	230.514
⅜	3460.2	208.523	½	4242.9	230.907
½	3473.2	208.916	⅝	4257 4	231.300
⅝	3486.3	209.309	¾	4271.8	231.692
¾	3499.4	209.701	⅞	4286.3	232.085
⅞	3512.5	210.094	74	4300.8	232.478
67	3525.7	210.487	⅛	4315.4	232.871
⅛	3538.8	210.879	¼	4329.9	233.263
¼	3552.0	211.272	⅜	4344.5	233.656
⅜	3565.2	211.665	½	4359.2	234.049
½	3578.5	212.058	⅝	4373.8	234.441
⅝	3591.7	212.450	¾	4388.5	234.334
¾	3605.0	212.843	⅞	4403.1	235.227
⅞	3618.3	213.236	75	4417.9	235.619
68	3631.7	213.628	⅛	4432.6	236.012
⅛	3645.0	214.021	¼	4447.4	236.405
¼	3658.4	214.414	⅜	4462.2	236.798
⅜	3671.8	214.806	½	4477.0	237.190
½	3685.3	215.199	⅝	4491.8	237.583
⅝	3698.7	215.592	¾	4506.7	237.976
¾	3712.2	215.984	⅞	4521.5	238.368
⅞	3725.7	216.337	76	4536.5	238.761
69	3739.3	216.770	⅛	4551.4	239.154
⅛	3752.8	217.163	¼	4566.4	239.546
¼	3766.4	217.555	⅜	4581.3	239.939
⅜	3780.0	217.948	½	4596.3	240.332
½	3793.7	218.341	⅝	4611.4	240.725
⅝	3807.3	218.733	¾	4626.4	241.117
¾	3821.0	219.126	⅞	4641.5	241.510
⅞	3834.7	219.519	77	4656.6	241.903
70	3848.5	219.911	⅛	4671.8	242.295
⅛	3862.2	220.304	¼	4686.9	242.688
¼	3876.0	220.697	⅜	4702.1	243.081

Table XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
77½	4717.3	243.473	84⅝	5624.5	265.857
⅝	4732.5	243.866	¾	5641.2	266.250
¾	4747.8	244.259	⅞	5657.8	266.643
⅞	4763.1	244.652	85	5674.5	267.035
78	4778.4	245.044	⅛	5691.2	267.428
⅛	4793.7	245.437	¼	5707.9	267.821
¼	4809.0	245.830	⅜	5724.7	268.213
⅜	4824.4	246.222	½	5741.5	268.606
½	4839.8	246.615	⅝	5758.3	268.999
⅝	4855.2	247.008	¾	5775.1	269.392
¾	4870.7	247.400	⅞	5791.9	269.784
⅞	4886.2	247.793	86	5808.8	270.177
79	4901.7	248.186	⅛	5825.7	270.570
⅛	4917.2	248.579	¼	5842.6	270.962
¼	4932.7	248.971	⅜	5859.6	271.355
⅜	4948.3	249.364	½	5876.5	271.748
½	4963.9	249.757	⅝	5893.5	272.140
⅝	4979.5	250.149	¾	5910.6	272.533
¾	4995.2	250.542	⅞	5927.6	272.926
⅞	5010.9	250.935	87	5944.7	273.319
80	5026.5	251.327	⅛	5961.8	273.711
⅛	5042.3	251.720	¼	5978.9	274.104
¼	5058.0	252.113	⅜	5996.0	274.497
⅜	5073.8	252.506	½	6013.2	274.889
½	5089.6	252.898	⅝	6030.4	275.282
⅝	5105.4	253.291	¾	6047.6	275.675
¾	5121.2	253.684	⅞	6064.9	276.067
⅞	5137.1	254.076	88	6082.1	276.460
81	5153.0	254.469	⅛	6099.4	276.853
⅛	5168.9	254.862	¼	6116.7	277.846
¼	5184.9	255.254	⅜	6134.1	277.638
⅜	5200.8	255.647	½	6151.4	278.031
½	5216.8	256.040	⅝	6168.8	278.424
⅝	5232.8	256.433	¾	6186.2	278.816
¾	5248.9	256.825	⅞	6203.7	279.209
⅞	5264.9	257.218	89	6221.1	279.602
82	5281.0	257.611	⅛	6238.6	279.994
⅛	5297.1	258.003	¼	6256.1	280.387
¼	5313.3	258.396	⅜	6273.7	280.780
⅜	5329.4	258.789	½	6291.2	281.173
½	5345.6	259.181	⅝	6308.8	281.565
⅝	5361.8	259.574	¾	6326.4	281.958
¾	5378.1	259.967	⅞	6344.1	282.351
⅞	5394.3	260.359	90	6361.7	282.743
83	5410.6	260.752	⅛	6379.4	283.136
⅛	5426.9	261.145	¼	6397.1	283.529
¼	5443.3	261.538	⅜	6414.9	283.921
⅜	5459.6	261.930	½	6432.6	284.314
½	5476.0	262.323	⅝	6450.4	284.707
⅝	5492.4	262.716	¾	6468.2	285.100
¾	5508.8	263.103	⅞	6486.0	285.492
⅞	5525.3	263.501	91	6503.9	285.885
84	5541.8	263.894	⅛	6521.8	286.278
⅛	5558.3	264.286	¼	6539.7	286.670
¼	5574.8	264.679	⅜	6557.6	287.063
⅜	5591.4	265.072	½	6575.5	287.456
½	5607.9	265.465	⅝	6593.5	287.848

TABLE XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 1 TO 100

Dia.	Area	Circum.	Dia.	Area	Circum.
91¾	6611.5	288.241	95⅞	7219.4	301.200
⅞	6629.6	288.634	96	7238.2	301.593
92	6647.6	289.027	⅛	7257.1	301.986
⅛	6665.7	289.419	¼	7276.0	302.378
¼	6683.8	289.812	⅜	7294.9	302.771
⅜	6701.9	290.205	½	7313.8	303.164
½	6720.1	290.597	⅝	7332.8	303.556
⅝	6738.2	290.990	¾	7351.8	303.949
¾	6756.4	291.383	⅞	7370.8	304.342
⅞	6774.7	291.775	97	7389.8	304.734
93	6792.9	292.168	⅛	7408.9	305.127
⅛	6811.2	292.561	¼	7428.0	305.520
¼	6829.5	292.954	⅜	7447.1	305.913
⅜	6847.8	293.346	½	7466.2	306.305
½	6866.1	293.739	⅝	7485.3	306.698
⅝	6884.5	294.132	¾	7504.5	307.091
¾	6902.9	294.524	⅞	7523.7	307.483
⅞	6921.3	294.917	98	7543.0	307.876
94	6939.8	295.310	⅛	7562.2	308.269
⅛	6958.2	295.702	¼	7581.5	308.661
¼	6976.7	296.095	⅜	7600.8	309.064
⅜	6995.3	296.488	½	7620.1	309.447
½	7013.8	296.881	⅝	7639.5	309.840
⅝	7032.4	297.273	¾	7658.9	310.232
¾	7051.0	297.666	⅞	7678.3	310.625
⅞	7069.6	298.059	99	7697.7	311.018
95	7088.2	298.451	⅛	7717.1	311.410
⅛	7106.9	298.844	¼	7736.6	311.803
¼	7125.6	299.237	⅜	7756.1	312.196
⅜	7144.3	299.629	½	7775.6	312.588
½	7163.0	300.022	⅝	7795.2	312.981
⅝	7181.8	300.415	¾	7814.8	313.374
¾	7200.6	300.807	⅞	7834.4	313.767

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 100 TO 250

Dia.	Area	Circum.	Dia.	Area	Circum.
100	7853.98	314.16	114	10207.03	358.14
101	8011.85	317.30	115	10386.89	361.28
102	8171.28	320.44	116	10568.32	364.42
103	8332.29	323.58	117	10751.32	367.57
104	8494.87	326.73	118	10935.88	370.71
105	8659.01	329.87	119	11122.02	373.85
106	8824.73	333.01			
107	8992.02	336.15	120	11309.73	376.99
108	9160.88	339.29	121	11499.01	380.13
109	9331.32	342.43	122	11689.87	383.27
			123	11882.29	386.42
110	9503.32	345.58	124	12076.28	389.56
111	9676.89	348.72	125	12271.85	392.70
112	9852.03	351.86	126	12468.98	395.84
113	10028.75	355.00	127	12667.69	398.98

Table XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 100 TO 250

Dia.	Area	Circum.	Dia.	Area	Circum.
128	12867.96	402.12	180	25446.90	565.49
129	13069.81	405.27	181	25730.43	568.63
130	13273.23	408.41	182	26015.53	571.77
131	13478.22	411.55	183	26302.20	574.91
132	13684.78	414.69	184	26590.44	578.05
133	13892.91	417.83	185	26880.25	581.19
134	14102.61	420.97	186	27171.63	584.34
135	14313.88	424.12	187	27464.59	587.48
136	14526.72	427.26	188	27759.11	590.62
137	14741.14	430.40	189	28055.21	593.76
138	14957.12	433.54	190	28352.87	596.90
139	15174.68	436.68	191	28652.11	600.04
140	15393.80	439.82	192	28952.92	603.19
141	15614.50	442.96	193	29255.30	606.33
142	15836.77	446.11	194	29559.25	609.47
143	16060.61	449.25	195	29864.77	612.61
144	16286.02	452.39	196	30171.86	615.75
145	16513.00	455.53	197	30480.52	618.89
146	16741.55	458.67	198	30790.75	622.04
147	16971.67	461.81	199	31102.55	625.18
148	17203.36	464.96	200	31415.93	628.32
149	17436.62	468.10	201	31730.87	631.46
150	17671.46	471.24	202	32047.39	634.60
151	17907.86	474.38	203	32365.47	637.74
152	18145.84	477.52	204	32685.13	640.88
153	18385.39	480.66	205	33006.36	644.03
154	18626.50	483.81	206	33329.16	647.17
155	18869.19	486.95	207	33653.53	650.31
156	19113.45	490.09	208	33979.47	653.45
157	19359.28	493.23	209	34306.98	656.59
158	19606.68	496.37	210	34636.06	659.73
159	19855.65	499.51	211	34966.71	662.88
160	20106.19	502.65	212	35298.94	666.02
161	20358.31	505.80	213	35632.73	669.16
162	20611.99	508.94	214	35968.09	672.30
163	20867.24	512.08	215	36305.03	675.44
164	21124.07	515.22	216	36643.54	678.58
165	21382.46	518.36	217	36983.61	681.73
166	21642.43	521.50	218	37325.26	684.87
167	21903.97	524.65	219	37668.48	688.01
168	22167.08	527.79	220	38013.27	691.15
169	22431.76	530.93	221	38359.63	694.29
170	22698.01	534.07	222	38707.56	697.43
171	22965.83	537.21	223	39057.07	700.58
172	23235.22	540.35	224	39408.14	703.72
173	23506.18	543.50	225	39760.78	706.86
174	23778.71	546.64	226	40115.00	710.00
175	24052.82	549.78	227	40470.78	713.14
176	24328.49	552.92	228	40828.14	716.28
177	24605.74	556.06	229	41187.07	719.42
178	24884.56	559.20	230	41547.56	722.57
179	25164.94	562.35	231	41909.63	725.71

TABLE XXVI—*Continued*

AREAS AND CIRCUMFERENCES OF CIRCLES FROM 100 TO 250

Dia.	Area	Circum.	Dia.	Area	Circum.
232	42273.27	728.85	241	45616.71	757.12
233	42638.48	731.99	242	45996.06	760.27
234	43005.26	735.13	243	46376.98	763.41
235	43373.61	738.27	244	46759.47	766.55
236	43743.54	741.42	245	47143.52	769.69
237	44115.03	744.56	246	47529.16	772.83
238	44488.09	747.70	247	47916.36	775.97
239	44862.73	750.84	248	48305.13	779.11
			249	48695.47	782.26
240	45238.93	753.98			

Table XXVIIa
PROPERTIES OF METALS[1]

	Theoretical Yield Points: Minimum* (commercially annealed)	Theoretical Yield Points: Maximum (severely cold-worked)	Reduction in area (maximum annealed)	Shearing Stress and Per Cent Penetration to Fracture: Annealed to soft temper		Shearing Stress and Per Cent Penetration to Fracture: Cold-worked to temper noted		Tensile Strength (nominal) annealed	Elongation in 2 inches (average) annealed	Elasticity Young's Modulus	Modulus of Strain Hardening (Tentative)	Bulk Modulus Volume	Annealing Temperature Approx. Commercial	Forging Temperature Approx	Thermal Coefficient of Expansion	Weight
	lb./sq in.	lb /sq.in.	%	lb /sq in	%	lb /sq in.	%	lb /sq in	%	lb /sq in	lb /sq in	lb /sq in	deg F.	deg F.	in./in./deg F	lb / cu.in
Aluminum, No. 2S comerc'ly pure	(4-) 8,000	H 21,000	80	8,000	60	H 13,000	30	13,000	35–45	10,300,000	25,000	10,200,000	650		0 000,010	0 0963
Aluminum, No. 3S, Mn. alloy	11,500	H 25,000	80	11,000		H 16,000		16,000	30–40	10,300,000	29,000		750			
Aluminum, No. 17S for heat treatm't	HT 30,000												630–650	400		
Aluminum, No. 52S, Cr. alloy	21,000	H 37,000	80	14,000		H 36,000		29,000	25–30	10,300,000	38,000		650			
Aluminum, No 61S, .25 Cu., .6 Si — 1 Mg.— .25Cr.	15,000	35,000	57					O 18,000 HT 42,000	O 22 HT 10	10,300,000						
Brass, yellow for cold working	(10-)40,000	95,000	75	32,000	50	? 52,000	20	50,000	65	13,400,000	120,000	8,800,000	1100			.303
Brass for forging, beta														12–1400		.301
Bronze, Tobin alloy	25,000	120,000	53	36,000	25	¼H 42,000	17	60,000	46		250,000					315
Copper	(10-)25,000	62,000	65	22,000	55			33,000	68	14,500,000	81,000	17,400,000		16–1800	000,009	3195
Gold				5,000						11,600,000		23,200,000	6–800		000,008	6949
Iron, cast, gray	8,000 tension 30,000 compr							23,000		12,000,000		13,900,000			000,005,5	260
Iron, cast, high test	15,000 tension 40,000 compr							45,000		20,000,000						
Lead	(1-) 3,000	4,000		3,500	50					2,470,000		1,100,000	below room temp		000,017	4106

TABLE XXVIIa—*Continued*

"Duronze" III 91 Cu—7 Al— 2 Si			45					85,000	35–45	14,000,000			1100–1200			.278
Magnesium, M. Alloy (Dow)	18,000	34,000		16,000				33,000	12–17	6,500,000			300	Dwg. 600 650		.063
Monel metal Nickel Silver	28,000 21,000 25,000	H 112,000 H 115,000 60,000	63 75	35,000	55			70,000 70,000 40,000	30–50 47 30–35	32,000,000 10,900,000		24,600,000 14,500,000	11–1200 12–1300 6–800		.000,007 000,010	318 .3175 .3791
Steel, 0.03C Armco .15C .50C 1.00C	(20-)35,000 (32-)55,000 (55-)70,000 90,000	70,000 110,000 145,000	76 60 45 20–40	34,000 48,000 71,000 115,000	60 38 24 10	61,000 90,000 150,000	25 14 2	42–48,000 57,000 85,000 120,000	48 35 25 10	30,000,000 30,000,000 30,000,000 30,000,000	100,000 150,000 200,000	23,200,000	13–1400 13–1400 13–1400	18–2100	000,009–16	.2834
Steel, electrical high-silicon				65,000	30											
Steel, stainless low-carbon for dwg. Enduro AA 18–8	50,000 (35-)50,000	120,000 165,000	60 71	57,000	39			80,000 95,000	25 57	30,000,000	400,000		13–1550 13–1900	19–2100 2100		.285
high-carbon for cutlery, etc.			32					260,000	11				1450–1600	20–2100	.000,006–7	
Tin	(2-) 4,000	4,500		5,000	40					7,260,000		7,260,000	below room temp 2–300		.000,015	.2652
Zinc	(12-)28,000		43	14,000	50	19,000	25	30–37,000	27	13,100,000		5,100,000			.000,014 5	.256
				Compression Molding Pressure		Compressive Strength						Powder to Solid-Ratio (Compression)		Sintering Temp. Deg. F.		
Powder Metallics Iron, porous	6,000- 20,000 compr.			15,000 100,000		40,000 140,000		12,000- 30,000				3+	1000	To 2050	000,007 .000,008	.199 .221
Bronze, porous	7,000			30,000		11,000 120,000		11,000				3+		1300 1700	.000,010,5	.22
Copper, dense				100,000				16,000- 49,000	1–27			3+		1200 1500	.000,009,2	.285 .317
Tungsten Carbide 3-20% co- balt binder	425,000- 785,000 compr.			400 2,500		550,000 815,000				80,000,000 97,000,000					.000,005 .000,006	.490 .550

* Figures in parenthesis represent laboratory test minimum which might prove misleading for estimating loads.
All physical values are subject to some variations with testing methods and analysis of material.
[1] Kent's "Mechanical Engineers' Handbook," 11th Edition, John Wiley & Sons, Inc., New York, 1938.

TABLE XXVIIID

PROPERTIES OF SYNTHETIC THERMOPLASTICS

	Yield Point at 77°F. approx.	Hot Shearing Temp. approx.	Knife Edge Cutting Load 77°F.	Shearing Strength 77°F.	Compression Molding Pressure	Injection Molding Pressure	Compressive Strength	Tensile Strength	Elongation in 2"	Powder to Solid Compression	Modulus of Elasticity	Lowest Recrystall'n Temp. approx.	Forming, C'pression Molding Temp. approx.	Injection Molding Temp. approx.	Thermal Coeff. of Expansion	Weight
	lb./sq.in.	deg. F.	lb./lin. in.	lb./sq.in.	lb./sq in.	lb./sq.in	lb./sq in.	lb /sq.in.	per cent	ratio	lb /sq in.	deg. F.	deg. F.	deg. F.	in./in./deg. F.	lb./cu. in
Cellulose Acetate	5,000	77+	400 500	6,000 10,000	500 5,000	3,000 30,000	5,000 27,000	2,200 14,600	7 3–43	2–2 6	300,000	30–40	250 350	300 420	0 000,044 000,088	0 045 .050
Cellulose Nitrate (Celluloid)		120 150	300 400		2,000 5,000		20,000 30,000	5,000 12,000	10–50		200,000 400,000		185 250		000,066 000,088	049 .050
Cellulose Acetate Butyrate				6,000	500 5,000	8,000 30,000	7,500 30,400	2,500 7,500	5–90	2 –2 8	200,000 350,000		260 370	340 420		
Ethyl Cellulose	1,500 3,500			7,500	1,500 5,000	3,000 30,000	10,000 12,000	2,000 9,000	10–40	2 2–2 5	100,000 500,000		300 360	350 425	000,055 000,077	.041
Methyl Methacrylate	7,000 9,000	200		11,500	2,000 7,500	10,000 35,000	10,000 12,500	6,000 9,000	1–5	1 7–2 2	300,000 500,000	100–110	280 350	325 475	000,036 000,052	0417 0435
Nylon (Molded)								5,000 8,500	30–35				450			
Vinyl Chloride								1,000 10,000			350,000 400,000				000,038	0486
Vinylidene Chloride	26,000			8,000 10,500	250 5,000	10,000 30,000	7,500 8,500	4,000 8,000	15–25		70,000 200,000	30–40	250 350	300 400	000,087	0595 0633
Polystyrene (Vinyl Benzene)				8,000	1,000 5,000	10,000 30,000	11,500 15,000	5,000 9,000	2–5	2–2 3	170,000 470,000	–76	275 350	300 500	000,033 000,044	038 .0385
Soluplastics Vulcanized Fiber		180	400	4,000			20,000 32,000	5,000 12,000								036 054
Aircraft Spruce (Douglas Fir)							5,000	10,000			1,300,000					017

Table XXVIIc

PROPERTIES OF THERMOSETTING MIXTURES

	Yield Point at 77°F. approx.	Hot Shearing Temp.	Knife Edge Cutting Load	Shearing Strength	Compression Molding Pressure	Injection Molding Pressure	Compressive Strength	Tensile Strength	Elongation in 2"	Powder to Solid Compression	Modulus of Elasticity	Lowest Recrystall'n Temp. approx.	Forming, C'pression Molding Temp.	Injection Molding Temp. approx.	Thermal Coeff. of Expansion	Weight
	p.s.i.	deg. F.	lb./lin. in.	p.s.i.	p.s.i.	p.s.i.	p.s.i.	p.s.i.	per cent	ratio	p.s.i.	deg. F.	deg. F.	deg. F.	in./in./deg. F.	lb./cu. in.
Phenol-Formaldehyde (no filler)		200 250		10,000	2,000 5,000		10,000 30,000	7,000 12,000	1.1	2 [illegible].6	700,000 1,000,000		300 340		0.000,013 .000,03	0.046
Phenol-Formaldehyde (wood flour filler)		200 250			2,000 4,500	2,000 10,000	16,000 36,000	6,000 11,000	.6	2 2–3.	1,000,000 1,500,000		280 360	275 375	.000,020 .000,041	.0481 .055
Phenol-Formaldehyde (mineral filler)		200 250			2,000 6,000	2,000 15,000	18,000 36,000	4,000 8,000	.6	2.–8.	1,000,000 4,500,000		270 350	275 350	.000,014 .000,02	.061 .075
Phenol-Formaldehyde (macerated fabric filler)		200 250			2,000 8,000		20,000 32,000	5,500 8,000	.7	2.5–15.	700,000 1,200,000		270 350		.000,01 .000,03	.049 .053
Phenol-Formaldehyde (sisal felt filler)		200 250			300 3,000	10,000 20,000	10,000 35,000	7,000 12,000		2 –5.			275 350	275 350	.000,1 .000,03	.025 .050
Phenol-Formaldehyde (paper laminate)	4,000 18,000	200 250		12,500	1,000 3,000		20,000 40,000	7,000 18,000	1.5	1.5–3	400,000 3,000,000		275 350		.000,009 .000,013	.047 .049
Phenol-Formaldehyde (cotton fabric laminate)	3,000 8,000	200 250		15,000	1,000 3,000		30,000 44,000	8,000 12,000	1–2	1.5–3.	350,000 1,500,000		275 350		.000,009 .000,01	.047 .049

TABLE XXVIIc—*Continued*

	Yield Point at 77°F. approx.	Hot Shearing Temp.	Knife Edge Cutting Load	Shearing Strength	Compression Molding Pressure	Injection Molding Pressure	Compressive Strength	Tensile Strength	Elongation in 2"	Powder to Solid Compression	Modulus of Elasticity	Lowest Recrystall'n Temp. approx.	Forming, C'pression Molding Temp.	Injection Molding Temp. approx.	Thermal Coeff. of Expansion	Weight
	p.s.i.	deg. F.	lb./lin. in.	p.s.i.	p.s.i.	p.s.i.	p.s.i.	p.s.i.	per cent	ratio	p.s.i.	deg. F.	deg. F.	deg. F.	in./in./ deg. F.	lb./cu. in.
Phenol-Formaldehyde (glass fabric laminate)	4,500 28,000	200 250			1,000 3,000		42,000 47,000	14,000 20,000	2		1,000,000 2,000,000		275 350			.050 .057
Phenol-Formaldehyde (asbestos cloth laminate)		200 250			1,000 3,000		18,000 45,000	7,000 12,000		1.6	350,000 1,500,000		300 350		.000,009 .000,013	.056 .066
Birch Plywood (phenolic binder)					200 2,000		5,700	13,100			1,400,000					.0288
Urea-Formaldehyde (alpha-cellulose filler)				13,000	1,500 6,000		20,000 24,000	5,500 7,000		2 5–3.	1,200,000 1,500,000		290 325		.000,013,8 .000,016	.052 .054
Urea-Formaldehyde (cotton fabric laminate)	600 2,500				1,500 6,000		7,000 8,700	5,100 6,900	8–22		560,000		290 325			.044
Melamine-Formaldehyde (alpha-cellulose filler)					1,500 6,000					2 0–2.3			280 340			.0537
Melamine-Formaldehyde (asbestos filler)					1,000 4,000		30,000	5,500 7,000	.30–.45	2.1–2.5	1,600,000		280 330		.000,01 .000,025	.0612 .067

TABLE XXVIIc—*Continued*

Aniline-Formaldehyde (no filler)					1,500 6,000		20,000 23,000	8,500 10,000		2.5–3.	500,000 600,000		300 340		.000,02 .000,03	.044 .045
Casein-Formaldehyde					2,000 2,500		5,300 27,000	10,000	2 5		510,000 570,000		200 225		.000,04	.0487
Phenol-Furfural (wood flour filler)					1,000 4,000	300 10,000	28,000 36,000	6,000 11,000		2.5–3	1,000,000 2,500,000		330 400	250 375	.000,01	.047 .050
Phenol-Furfural (mineral filler)					1,000 4,000	300 15,000	24,000 36,000	5,000 10,000		2.5–6.	1,000,000 [illegible],500,000		330 360	250 375	.000,01	.057 .072
Phenol-Furfural (fabric filler)					1,000 8,000	300 30,000	26,000 30,000	6,500 8,000		4 15	700,000 1 200,000		300 360	250 375	.000,025	047 .050
Phenol-Lignin (laminate)					1,500 2,000		25,000 30,000	7,500 12,000		2 –3	800,000 2,000,000		365		.000,011 .000,013	.049 .051
Columbia Allyl Resin 39 (paper laminate)							15,000 31,000	10,000 21,000								.048
Columbia Allyl Resin 39 (fabric laminate)							29,000	1,000 7,500	4.		550,000		160 240		.000,013 .000,023	.048
Columbia Allyl Resin 39 (glass cloth l'inate)	12,700						52,000 60,000	30,400 39,000			1,700,000		160 240		.000,01	.062
Columbia Allyl Resin 39 (Sheet)								6,000			350,000	140	160 240		000,049	.047
Shellac					1,000 2,500	1,000 1,200	10,000 17,000	900 2,000		2 –3.	500,000 600,000		240	180 260		.039 098
Rubber-Sulphur								1,000 4,000	600		400					035 .045
Ceramic "Prestite" (flint, feldspar, ball clay, china clay)					3,000 5,000		48,000	5,000			10,000,000	1,200			.000,002 .000,006	.088

Table XXVIII

SHEET METAL AND WIRE GAUGES

Gauge No.	American or Brown & Sharpe	Birmingham or Stubs	Washburn & Moen	Imperial S. W. G.	London or Old English	Sheet Zinc Gauge	American Russia Iron	U. S. Standard: Thickness in Decimal Parts of an Inch	U. S. Standard: Thickness in Fraction of an Inch	U. S. Standard: Thickness in Millimeters	Gauge No.
	*1	*2	*3					*4			
0000000	....	....	0.490	0.500	....	....	....	0.5	1/2	12.7	0000000
000000	0.5800	....	.460	.464	....	....	....	.46875	15/32	11.90625	000000
00000	.5165	....	.430	.432	....	....	....	.4375	7/16	11.1125	00000
0000	.4600	0.454	.3938	.400	0.454	....	....	.40625	13/32	10.31875	0000
000	.4096	.425	.3625	.372	.425	....	....	.375	3/8	9.525	000
00	.3648	.380	.3310	.348	.38	....	....	.34375	11/32	8.73125	00
0	.3249	.340	.3065	.324	.34	....	....	.3125	5/16	7.9375	0
						No. In.					
1	.2893	.300	.2830	.300	.3	1 = 0 002	....	.28125	9/32	7.14375	1
2	.2576	.284	.2625	.276	.284	2 = 0.004	....	.265625	17/64	6.746875	2
3	.2294	.259	.2437	.252	.259	3 = 0.006	....	.25	1/4	6.35	3
4	.2043	.238	.2253	.232	.238	4 = 0.008	....	.234375	15/64	5.953125	4
5	.1819	.220	.2070	.212	.22	5 = 0.010	....	.21875	7/32	5.55625	5
6	.1620	.203	.1920	.192	.203	6 = 0.012	No. In.	.203125	13/64	5.159375	6
7	.1443	.180	.1770	.176	.18	7 = 0.014	7 = 0.015	.1875	3/16	4.7625	7
8	.1285	.165	.1620	.160	.165	8 = 0.016	8 = 0.016	.171875	11/64	4.365625	8
9	.1144	.148	.1483	.144	.148	9 = 0.018	9 = 0.017	.15625	5/32	3.96875	9
10	.1019	.134	.1350	.128	.134	10 = 0.020	10 = 0.018	.140625	9/64	3.571875	10
11	.09074	.120	.1205	.116	.12	11 = 0.024	11 = 0.020	.125	1/8	3.175	11
12	.08081	.109	.1055	.104	.109	12 = 0.028	12 = 0.021	.109375	7/64	2 778125	12
13	.07196	.095	.0915	.092	.095	13 = 0.032	13 = 0.024	.09375	3/32	2.38125	13
14	.06408	.083	.0800	.080	.083	14 = 0.036	14 = 0.025	.078125	5/64	1.984375	14
15	.05707	.072	.0720	.072	.072	15 = 0.040	15 = 0.027	.0703125	9/128	1.7859375	15
16	.05082	.065	.0625	.064	.065	16 = 0.045	16 = 0.030	.0625	1/16	1.5875	16
17	.04526	.058	.0540	.056	.058	17 = 0.050	....	.05625	9/160	1.42875	17
18	.04030	.049	.0475	.043	.049	18 = 0.055	....	.05	1/20	1.27	18
19	.03589	.042	.0410	.040	.040	19 = 0.060	....	.04375	7/160	1.11125	19
20	.03196	.035	.0348	.036	.035	20 = 0.070	....	.0375	3/80	0.9525	20

21	02846	032	03175	032	0315	21 = 0 080		034375	11 320	873125	21
22	02535	028	0286	028	0295	22 = 0 090		03125	1 32	79375	22
23	02257	025	0258	024	027	23 = 0 100		028125	9 320	714375	23
24	02010	022	0230	022	025	24 = 0 125		025	1 40	635	24
25	01790	020	0204	020	023	25 = 0 250		021875	7 320	555625	25
26	01594	018	0181	018	0205	26 = 0 375		01875	3 160	47625	26
27	01420	016	0173	0164	0187	27 = 0 500		0171875	11 640	4365625	27
28	01264	014	0162	0148	0165	28 = 1 000		015625	1 64	396875	28
29	01126	013	0150	0136	0155			0140625	9 640	3571875	29
30	01003	012	0140	0124	.01372			0125	1 80	3175	30
31	008928	010	0132	0116	0122			0109375	7 640	2778125	31
32	007950	009	0128	0108	0112			01015625	13 1280	25796875	32
33	007080	008	0118	0100	0102			009375	3 320	238125	33
34	006305	007	0104	0092	0095			00859375	11 1280	21828125	34
35	005615	005	0095	0084	009			0078125	5 640	1984375	35
36	005000	004	0090	0076	0075			00703125	9 1280	17859375	36
37	004453		0085	0068	0065			006640625	17/2560	168671875	37
38	003965		008	0060	0057			00625	1 160	15875	38
39	003531		0075	0052	005						39
40	003145		007	0048	0045						40
41	002800			0044							41
42	002494			004							42
43	002221			0036							43
44	001978			0032							44
45	001761			0028							45
46	001568			0024							46
47	001397			002							47
48	001244			0016							48
49	001018			0012							49
50	0009863			001							50

* American uses of different guages

1 American or Brown & Sharpe gauge,
  Aluminum, except tubing—2,
  Brass tubing below 3/8 in , O D ,
  Brass sheets, strips and wire,
  Copper sheets and wire,
  Nickel-silver sheets and wire,
  Phosphor-bronze strip
2 Birmingham or Stubs gauge,
  Aluminum tubing (only),
  Steel tubing, seamless and welded,
  Brass tubing, 3/8 in O D and over,
  Flat wire,
  Steel hoops,
  Spring steel,
  Strip steel
3 Washburn & Moen gauge,
  Steel wire (except music wire, flat wire, armature wire).
4. U S Standard gauge
  Steel sheets and plates,
  Nickel sheets

Table XXIX

TIN-PLATE DATA

Trade Term		80-lb.	85-lb.	90-lb.	95-lb.	100-lb.
Nearest U. S. Gauge		33	32	31	31	30½
Decimal Equivalent		.008	.009	.010	.010	.012
Weight, Sq. Ft., Lbs.		.367	.390	.413	.436	.459
Size of Sheets	Sheets per Box	Net Weight per Box, Pounds				
10 x 14 Base	225	80	85	90	95	100
14 x 20 Base	112	80	85	90	95	100
20 x 28	112	160	170	180	190	200
10 x 20	225	114	121	129	136	143
11 x 22	225	138	147	156	164	172
11½ x 23	225	151	161	170	179	189
12 x 12	225	82	87	93	98	103
12 x 24	112	82	87	93	98	103
13 x 13	225	97	103	109	115	121
13 x 26	112	97	103	109	115	121
14 x 14	225	112	119	126	133	140
14 x 28	112	112	119	126	133	140
15 x 15	225	129	137	145	153	161
16 x 16	225	146	155	165	174	183
17 x 17	225	165	175	186	196	206
18 x 18	112	93	98	104	110	116
19 x 19	112	103	110	116	122	129
20 x 20	112	114	121	129	136	143
21 x 21	112	126	134	142	150	158
22 x 22	112	138	147	156	164	172
23 x 23	112	151	161	170	179	189
24 x 24	112	164	175	185	195	204
26 x 26	112	193	205	217	229	241
16 x 20	112	91	97	103	109	114
14 x 31	112	124	132	140	147	155
11¼ x 22¾	112	73	78	82	87	91
13¼ x 17¾	112	67	71	76	80	84
13¼ x 19¾	112	73	77	82	87	91
13½ x 19½	112	75	80	85	89	94
13½ x 19¾	112	76	81	86	90	95
14 x 18¾	124	83	88	93	98	103
14 x 19¼	120	83	88	93	98	103
14 x 21	112	84	89	95	100	105
14 x 22	112	88	94	99	105	110
14 x 22¼	112	89	95	100	106	111
15½ x 23	112	102	108	115	121	127

TABLE XXIX—*Continued*

TIN-PLATE DATA

Trade Term		IC	IXL	IX	IXX	IXXX	IXXXX
Nearest U. S. Gauge		30	28	28	26½	25½	25
Decimal Equivalent		.012	.014	.014	.016	.018	.020
Weight, Sq. Ft., Lbs.		.491	.588	.619	.712	.803	.895
Size of Sheets	Sheets per Box	Net Weight per Box, Pounds					
10 x 14 Base	225	107	128	135	155	175	195
14 x 20 base	112	107	128	135	155	175	195
20 x 28	112	214	256	270	310	250	390
10 x 20	225	153	183	193	221	250	279
11 x 22	225	184	222	234	268	302	337
11½ x 23	225	202	242	255	293	331	368
12 x 12	225	110	132	139	159	180	201
12 x 24	112	110	132	139	159	180	201
13 x 13	225	129	154	163	187	211	235
13 x 26	112	129	154	163	187	211	235
14 x 14	225	150	179	189	217	245	273
14 x 28	112	150	179	189	217	245	273
15 x 15	225	172	206	217	249	281	313
16 x 16	225	196	234	247	283	320	357
17 x 17	225	221	264	279	320	361	403
18 x 18	112	124	148	156	179	202	226
19 x 19	112	138	165	174	200	226	251
20 x 20	112	153	183	193	221	250	279
21 x 21	112	169	202	213	244	276	307
22 x 22	112	184	221	234	268	302	337
23 x 23	112	202	242	255	293	331	368
24 x 24	112	220	263	278	319	360	401
26 x 26	112	258	309	326	374	422	471
16 x 20	112	122	146	154	177	200	223
14 x 31	112	166	198	209	240	271	302
11¼ x 22¾	112	98	...	...	...	...	...
13¼ x 17¾	112	90	...	...	...	...	...
13¼ x 19¾	112	97	...	...	...	...	...
13½ x 19½	112	100	...	...	...	...	...
13½ x 19¾	112	102	...	...	...	...	...
14 x 18¾	124	110	...	...	...	...	...
14 x 19¼	120	110	...	...	...	...	...
14 x 21	112	112	...	...	...	...	...
14 x 22	112	118	...	...	...	...	...
14 x 22¼	112	119	...	...	...	...	...
15½ x 23	112	136	...	...	...	...	...

Table XXX*—Part 1

APPROXIMATE CAPACITIES OF STRAIGHT-SIDE SINGLE-CRANK PRESSES

Stroke of Press			3	4	5	6	8	10	12	14	16	18	20	22
Shaft Diameter	Type of Drive	At Bottom	Approximate Capacity in Tons at Midstroke											
1	Single	3												
1½	Single	6.75	3	2¼										
2	Single	12	7½	5½	4½									
2½	Single	19	14	11	8½	7								
3	Single	32	20	15	12	9	8							
3½	Single	44	31½	23½	19	16	14	11½						
4	Single	58	44	36	30	24	18	13	9					
4½	Single	74	60	50	40	35	26	19	12					
5	Single	93	73	64	56	47	35	28	22	18	14			
6	Single	135		108	94	80	60	48	39	35	32	30	27	
7	Single	190			135	122	98	78	69	62	46	36	31	
8	Single	255				174	147	117	98	82	70	55	45	37
8	Twin	255					225	196	162	142	121	110	95	85
9	Single	345			265	245	205	163	135	125	115	91	75	63
9	Twin	345						274	227	193	169	152	135	120
10	Single	440				340	282	227	185	150	123	117	111	105
10	Twin	440						354	310	267	233	206	185	166
11	Single	545				450	376	300	252	210	180	170	159	145
11	Twin	545						450	410	362	332	278	250	225
12	Single	665					485	390	320	280	240	210	190	170
12	Twin	665						550	510	460	405	360	325	285
13	Single	790					595	500	415	350	300	250	220	195
13	Twin	790							605	570	515	461	427	376
14	Single	920					707	615	510	460	380	310	280	250
14	Twin	920							737	700	630	565	510	465

Note: The above tonnages of pressure ratings are entirely independent of work or energy ratings. A long stroke press, if loaded to maximum pressure capacity through its maximum working stroke, will undoubtedly require additional flywheel and motor capacity.

* Reprinted, by permission, from Kent's "Mechanical Engineers' Handbook." See note, p. 425

Table XXX—Part 2

APPROXIMATE CAPACITIES OF STRAIGHT-SIDE DOUBLE-CRANK PRESSES

Stroke of Press			3	4	5	6	8	10	12	14	16	18	20	22
Shaft Diameter	Type of Drive	At Bottom	Approximate Capacity in Tons at Midstroke											
2½	Single	19	16	12	8									
3	Single	32	20	15	13	10	5							
3½	Single	44	31	23	19	16	9							
4	Single	58	41	33	29	22	19	12						
4½	Single	74	59	51	40	34	25	19						
5	Single	93	73	64	56	47	36	28	21					
6	Single	135		101	91	82	60	48	39					
7	Single	200			135	122	102	76	66	54				
8	Single	290				180	145	117	99	72	68			
8	Twin	290				260	230	196	160	140	120	108	96	
9	Single	400				250	205	165	137	110	98	90	85	
9	Twin	400				333	310	273	227	195	170	150	133	
10	Single	525				340	285	227	187	155	144	128	112	
10	Twin	525						375	315	265	233	205	185	170
11	Single	700				450	375	305	205	200	190	175	152	135
11	Twin	700						470	420	365	315	275	250	225
12	Single	900				580	485	390	325	270	240	223	192	185
12	Twin	900						610	540	470	410	360	320	290
13	Single	1150				740	621	498	415	355	315	285	250	235
13	Twin	1150						800	700	630	520	470	430	385
14	Single	1400				900	770	610	510	425	380	350	310	275
14	Twin	1400						958	850	730	640	565	510	455

Note: The above or tonnage pressure ratings are entirely independent of work or energy ratings. A long stroke press, if loaded to maximum pressure capacity through its maximum working stroke, will undoubtedly require additional flywheel and motor capacity.

Table XXXI

SQUARES, CUBES, SQUARE ROOTS AND CUBE ROOTS

1 to 200

No.	Squares	Cubes	Square Roots	Cube Roots
1	1	1	1 0000	1 0000
2	4	8	1 4142	1 2599
3	9	27	1 7321	1 4422
4	16	64	2 0000	1 5874
5	25	125	2 2361	1 7100
6	36	216	2 4494	1 8171
7	49	343	2 6457	1 9129
8	64	512	2 8284	2 0000
9	81	729	3 0000	2 0800
10	100	1000	3 1622	2 1544
11	121	1331	3 3166	2 2239
12	144	1728	3 4641	2 2894
13	169	2197	3 6055	2 3513
14	196	2744	3 7416	2 4101
15	225	3375	3 8729	2 4662
16	256	4096	4 0000	2 5198
17	289	4913	4 1231	2 5712
18	324	5832	4 2426	2 6207
19	361	6859	4 3588	2 6684
20	400	8000	4 4721	2 7144
21	441	9261	4 5825	2 7589
22	484	10648	4 6904	2 8020
23	529	12167	4 7958	2 8434
24	576	13824	4 8989	2 8844
25	625	15625	5 0000	2 9240
26	676	17576	5 0990	2 9624
27	729	19683	5 1961	3 0000
28	784	21952	5 2915	3 0365
29	841	24389	5 3851	3 0723
30	900	27000	5 4772	3 1072
31	961	29791	5 5677	3 1413
32	1024	32768	5 6568	3 1748
33	1089	35937	5 7445	3 2075
34	1156	39304	5 8309	3 2396
35	1225	42875	5 9160	3 2710
36	1296	46656	6 0000	3 3019
37	1369	50653	6 0827	3 3322
38	1444	54872	6 1644	3 3619
39	1521	59319	6 2444	3 3912
40	1600	64000	6 3245	3 4199
41	1681	68921	6 4031	3 4482
42	1764	74088	6 4807	3 4760
43	1849	79507	6 5574	3 5033
44	1936	85184	6 6332	3 5303
45	2025	91125	6 7082	3 5568
46	2116	97336	6 7823	3 5830
47	2209	103823	6 8556	3 6088
48	2304	110592	6 9282	3 6342
49	2401	117649	7 0000	3 6593
50	2500	125000	7 0710	3 6840

TABLE XXXI—*Continued*

SQUARES, CUBES, SQUARE ROOTS AND CUBE ROOTS

1 to 200

No.	Squares	Cubes	Square Roots	Cube Roots
51	2601	132651	7 1414	3 7084
52	2704	140608	7 2111	3 7325
53	2809	148877	7 2801	3 7562
54	2916	157464	7 3485	3 7798
55	3025	166375	7 4162	3 8030
56	3136	175616	7 4833	3 8259
57	3249	185193	7 5498	3 8485
58	3364	195112	7 6158	3 8709
59	3481	205379	7 6811	3 8930
60	3600	216000	7 7460	3 9149
61	3721	226981	7 8102	3 9365
62	3844	238328	7 8740	3 9579
63	3969	250047	7 9373	3 9791
64	4096	262144	8 0000	4 0000
65	4225	274625	8 0623	4 0207
66	4356	287496	8 1240	4 0412
67	4489	300763	8 1854	4 0615
68	4624	314432	8 2462	4.0817
69	4761	328509	8 3066	4 1016
70	4900	343000	8 3666	4 1213
71	5041	357911	8 4261	4 1408
72	5184	373248	8 4853	4 1602
73	5329	389017	8 5440	4 1793
74	5476	405224	8 6023	4 1983
75	5625	421875	8 6603	4 2172
76	5776	438976	8 7178	4 2358
77	5929	456533	8 7750	4 2543
78	6084	474552	8 8318	4 2727
79	6241	493039	8 8882	4 2908
80	6400	512000	8 9443	4 3089
81	6561	531441	9 0000	4 3267
82	6724	551368	9 0554	4 3445
83	6889	571787	9 1104	4 3621
84	7056	592704	9 1652	4 3795
85	7225	614125	9 2195	4 3968
86	7396	636056	9 2736	4 4140
87	7569	658503	9 3276	4 4310
88	7744	681472	9 3808	4 4480
89	7921	704969	9 4340	4 4647
90	8100	729000	9 4868	4 4814
91	8281	753571	9 5394	4 4979
92	8464	778688	9 5917	4 5144
93	8649	804357	9 6437	4 5307
94	8836	830584	9 6954	4 5468
95	9025	857375	9.7468	4 5629
96	9216	884736	9.7980	4 5789
97	9409	912673	9 8489	4 5947
98	9604	941192	9 8995	4 6104
99	9801	970299	9 9499	4 6261
100	10000	1000000	10 0000	4 6416

Table XXXI—*Continued*

SQUARES, CUBES, SQUARE ROOTS AND CUBE ROOTS
1 to 200

No.	Squares	Cubes	Square Roots	Cube Roots
101	10201	1030301	10.0499	4.6570
102	10404	1061208	10.0995	4.6723
103	10609	1092727	10.1489	4.6875
104	10816	1124864	10.1980	4.7027
105	11025	1157625	10.2470	4.7177
106	11236	1191016	10.2956	4.7326
107	11449	1225043	10.3441	4.7475
108	11664	1259712	10.3923	4.7622
109	11881	1295029	10.4403	4.7769
110	12100	1331000	10.4881	4.7914
111	12321	1367631	10.5357	4.8059
112	12544	1404928	10.5830	4.8203
113	12769	1442897	10.6301	4.8346
114	12996	1481544	10.6771	4.8488
115	13225	1520875	10.7238	4.8629
116	13456	1560896	10.7703	4.8770
117	13689	1601613	10.8167	4.8910
118	13924	1643032	10.8628	4.9049
119	14161	1685159	10.9087	4.9187
120	14400	1728000	10.9545	4.9324
121	14641	1771561	11.0000	4.9461
122	14884	1815848	11.0454	4.9597
123	15129	1860867	11.0905	4.9732
124	15376	1906624	11.1355	4.9866
125	15626	1953125	11.1803	5.0000
126	15876	2000376	11.2250	5.0133
127	16129	2048383	11.2694	5.0265
128	16384	2097152	11.3137	5.0397
129	16641	2146689	11.3578	5.0528
130	16900	2197000	11.4018	5.0658
131	17161	2248091	11.4455	5.0788
132	17424	2299968	11.4891	5.0916
133	17689	2352637	11.5326	5.1045
134	17956	2406104	11.5758	5.1172
135	18225	2460375	11.6190	5.1299
136	18496	2515456	11.6619	5.1426
137	18769	2571353	11.7047	5.1551
138	19044	2628072	11.7473	5.1676
139	19321	2685619	11.7898	5.1801
140	19600	2744000	11.8322	5.1925
141	19881	2803221	11.8743	5.2048
142	20164	2863288	11.9164	5.2171
143	20449	2924207	11.9583	5.2293
144	20736	2985984	12.0000	5.2415
145	21025	3048625	12.0416	5.2536
146	21316	3112136	12.0830	5.2656
147	21609	3176523	12.1244	5.2776
148	21904	3241792	12.1655	5.2896
149	22201	3307949	12.2066	5.3015
150	22500	3375000	12.2474	5.3133

Table XXXI—*Continued*

SQUARES, CUBES, SQUARE ROOTS AND CUBE ROOTS
1 to 200

No.	Squares	Cubes	Square Roots	Cube Roots
151	22801	3442951	12.2882	5.3251
152	23104	3511808	12.3288	5.3368
153	23409	3581577	12 3693	5 3485
154	23716	3652264	12.4097	5 3601
155	24025	3723875	12.4499	5 3717
156	24336	3796416	12.4900	5.3832
157	24649	3869893	12.5300	5 3947
158	24964	3944312	12.5698	5.4061
159	25281	4019679	12.6095	5.4175
160	25600	4096000	12.6491	5.4288
161	25921	4173281	12.6886	5.4401
162	26244	4251528	12.7279	5.4514
163	26569	4330747	12.7671	5.4626
164	26896	4410944	12.8062	5.4737
165	27225	4492125	12 8452	5.4848
166	27556	4574296	12.8841	5.4959
167	27889	4657463	12.9228	5.5069
168	28224	4741632	12.9615	5 5178
169	28561	4826809	13.0000	5.5288
170	28900	4913000	13.0384	5.5397
171	29241	5000211	13.0767	5.5505
172	29584	5088448	13.1149	5.5613
173	29929	5177717	13.1529	5 5721
174	30276	5268024	13.1909	5.5828
175	30625	5359375	13 2288	5.5934
176	30976	5451776	13.2665	5.6041
177	31329	5545233	13.3041	5.6147
178	31684	5639752	13.3417	5.6252
179	32041	5735339	13.3791	5.6357
180	32400	5832000	13.4164	5.6462
181	32761	5929741	13.4536	5.6567
182	33124	6028568	13.4907	5.6671
183	33489	6128487	13.5277	5.6774
184	33856	6229504	13.5647	5.6877
185	34225	6331625	13.6015	5.6980
186	34596	6434856	13.6382	5.7083
187	34969	6539203	13.6748	5.7185
188	35344	6644672	13.7113	5.7287
189	35721	6751269	13.7477	5.7388
190	36100	6859000	13.7840	5.7489
191	36481	6967861	13.8203	5.7590
192	36864	7077888	13.8564	5.7690
193	37249	7189057	13.8924	5.7790
194	37636	7301384	13.9284	5.7890
195	38025	7414875	13.9642	5.7989
196	38416	7529536	14.0000	5.8088
197	38809	7645373	14.0357	5.8186
198	39204	7762392	14.0712	5.8285
199	39601	7880599	14.1067	5.8383
200	40000	8000000	14.1421	5.8480

Table XXXII

STEEL PIPE DATA

Size	External Dia.		Standard			X Heavy			XX Heavy			Seamless Tube *	Tap Drill			Parr. Thd's Root Dia.	Threads		Minimum Bending Radii in Inches for Std. Pipe
	Decimal	Approx. Fraction	Inside Dia.	Int. Area in Sq. In.	*	Inside Dia.	Int. Area in Sq. In.	*	Inside Dia.	Int. Area in Sq. In.	*		Taper Thd's Dia. Drill	Taper Thd's Depth of Drill	Parr. Thd's Dia. Drill		Engaged Length Req. for Tight Joint	Per Inch	
1/8	0.405	13/32	0.27	0.06	2500	0.22	0.04	3500				6000	11/32	5/8	23/64	0.345	5/16	27	
1/4	0.540	17/32	0.36	0.10	2500	0.30	0.07	3500				6000	7/16	13/16	15/32	0.445	7/16	18	
3/8	0.675	43/64	0.49	0.19	1500	0.42	0.14	2500				6000	37/64	7/8	39/64	0.583	7/16	18	
1/2	0.840	27/32	0.62	0.30	1500	0.55	0.23	2500	0 25	0.05	5000	6000	23/32	1	3/4	0.721	9/16	14	
3/4	1.050	1 3/64	0.82	0.53	1500	0.74	0.43	2000	0.43	0.15	4000	6000	59/64	1	61/64	0.932	9/16	14	
1	1.315	1 5/16	1.05	0.86	1500	0.96	0.72	2000	0.60	0.28	4000	6000	1 5/32	1 1/4	1 13/64	1.169	11/16	11 1/2	
1 1/4	1.660	1 21/32	1.38	1.50	1000	1.28	1.28	1500	0.90	0.63	3000	4000	1 1/2	1 1/4	1 35/64	1.514	11/16	11 1/2	
1 1/2	1.900	1 57/64	1.61	2.04	1000	1.50	1.77	1500	1 10	0.95	3000	4000	1 47/64	1 1/4	1 25/32	1.753	11/16	11 1/2	
2	2.375	2 3/8	2.07	3.36	750	1.94	2.95	1250	1.50	1.77	2500	4000	2 7/32	1 5/16	2 17/64	2.227	3/4	11 1/2	
2 1/2	2.875	2 7/8	2.47	4.79	750	2.32	4.24	1250	1.77	2.46	2500	4000	2 5/8	1 3/4	2 23/32	2 662	1 1/16	8	10
3	3.500	3 1/2	3.07	7.39	750	2 90	6.61	1250	2 30	4 16	3000	3500	3 1/4	1 13/16	3 11/32	3.288	1 1/8	8	12
3 1/2	4.000	4	3.55	9.89	1000	3.36	8.89	1500	2.73	5.85	3000	3500	3 3/4		3 27/32	3.789		8	14
4	4.500	4 1/2	4.03	12 73	1000	3.83	11.50	1250	3.15	7.80	2500	3000	4 1/4		4 11/32	4.287		8	16
5	5.563	5 9/16	5.05	20.01	750	4.81	18.19	1250	4.06	12.97	2500	3000			5 13/32	5.349		8	20
6	6.625	6 5/8	6.07	28.89	750	5.76	26.07	1250	4 90	18.84	2500	2500			6 9/64	6.406		8	24
7	7.625	7 5/8	7.02	38.74	650	6 63	34.47	1000	5 88	27.11	2000	2500			7 29/64	7.402		8	28
8	8.625	8 5/8	7.98	50.02	650	7 63	45.66	1000	6.88	37.12	2000	2000			8 9/64	8 400		8	32
9	9.625	9 5/8	8.94	62.79	650	8.63	58.43	1000							9 29/64	9.398		8	36
10	10.750	10 3/4	10.02	78.85	500	9.75	74 66	750							10 37/64	10.521		8	40
12	12.750	12 3/4	12.00	113.10	500	11.75	108.40	750							12 9/16	12.518		8	48
14	15.000	15	14.25	159.50	450	14.00	153.90	600							14 27/32	14 800		8	68

* Pipe serviceable for pressure indicated. If subjected to severe shocks, reduce service pressure to 75% that shown.

Table XXXIII

HYDRAULIC PIPE SELECTION

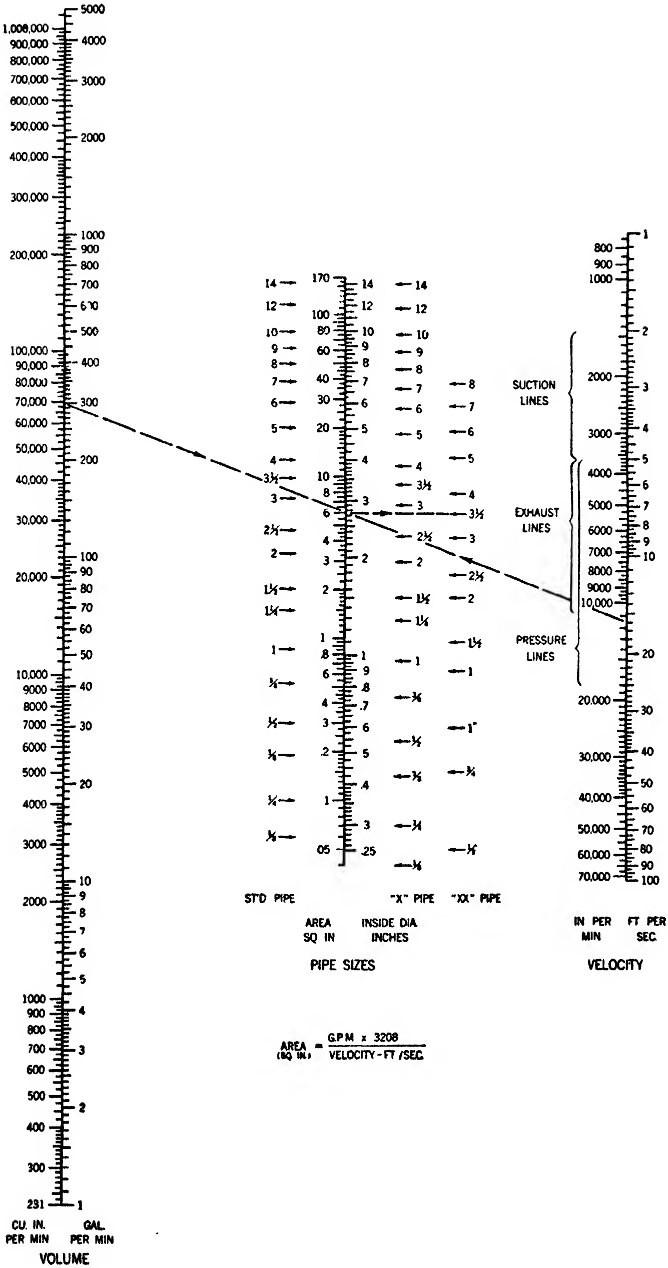


TABLE XXXIV

CAPACITIES OF HYDRAULIC PRESSES

Ram Dia.	Working Pressure, P.S.I. — Capacity in Tons: 300	500	600	750	1000	1200	1500	1800	2000	2250	2500	2750	3000	3250	3500	4000	4500	5000	5500	6000	6500	7000	Gals. per 1" Stroke	Gals. per Ft. Stroke	Area
2	.47	.8	.94	1.2	1.6	1.88	2.4	2.82	3.2	3.6	4	4.3	4.7	5.1	5.5	6.4	7.2	8	8.6	9.4	10	11	.013	.163	3.14
3	1.05	1.7	2.10	2.5	3.4	4.20	5.3	6.3	7.0	7.8	8.5	9.6	10.5	11.4	12	13.6	15.9	17	19.3	21	22	24.5	.030	.364	7.06
4	1.88	3.1	3.76	4.7	6.2	7.52	9.4	11.28	12.4	14	15.5	17	18.8	20.5	22	24.8	28	31	34.5	37.6	41	44	.054	.650	12.58
5	2.94	4.9	5.88	7.4	9.8	11.76	14.8	17.6	19.6	22	24.5	27	29.5	31.5	34	39	44	49	54	59	63	69	.087	1.02	19.64
6	4.25	7.1	8.50	10.9	14.2	17	21.8	25.5	28	32	35.5	39	42.5	45	49	56	65	71	78	85	90	99	.122	1.47	28.27
7	5.73	9.5	11.46	14.3	19	22.92	28.5	34.38	38	43	47.5	52	57	62	67	76	85	95	105	114	124	134	.167	2.00	38.48
8	7.50	12.5	15	18.7	25	30	37.5	45	50	56	62.5	69	75	85	92	100	112	125	138	150	170	184	227	2.73	50.26
9	9.55	16	19.10	23.7	32	38	47.5	57	64	71	80	87	95	104	112	128	142	160	174	190	208	223	277	3.30	63.62
10	11.8	19.6	23.6	29.5	39	47	59	71	78	88	98	108	118	128	137	156	172	195	217	236	256	275	.341	4.10	78.54
11	14.2	23.6	28.4	35.5	47	56	71	84	94	106	118	130	142	154	166	188	213	235	260	284	308	332	410	4.92	95.00
12	17	28	34	42	56	68	84	102	112	126	140	155	169	183	197	224	252	280	310	338	366	395	.487	5.85	113
13	19.9	33	39.8	49.5	66	79	99	119	132	148	165	186	198	214	230	264	297	330	362	396	428	460	571	6.85	132
14	23	38	46	57.5	76	92	115	138	152	172	190	210	230	250	270	304	345	380	420	460	500	540	.667	8.00	154
15	25.4	44	50.8	66	88	101	132	153	176	199	220	242	264	285	307	352	396	440	484	528	570	615	.775	9.30	176
16	30	50	60	75	100	120	150	180	200	225	250	275	300	325	350	400	450	500	550	600	650	700	.867	10.40	201
17	34	56	68	85	112	136	170	204	224	255	280	313	340	370	397	448	510	560	625	680	740	795	.983	11.80	227
18	38	63	76	95	126	152	190	228	252	285	315	349	380	414	445	504	570	630	698	760	828	890	1.10	13.20	254
19	42.5	71	85	106	142	170	212	255	284	318	355	388	425	460	495	568	636	710	775	850	920	990	1.22	14.64	283
20	47	78	94	117.5	156	188	235	282	312	352	390	430	470	510	550	624	705	780	860	940	1020	1100	1.36	16.32	314
21	52	86	104	130	172	208	260	312	344	390	430	475	520	560	605	688	780	860	950	1040	1120	1210	1.50	18.00	346
22	57	95	114	143	190	228	285	342	380	429	475	521	570	620	665	760	855	950	1042	1140	1240	1330	1.64	19.68	380
23	62	103	124	155	206	248	310	372	412	465	515	570	621	675	729	824	930	1030	1140	1242	1350	1458	1.80	21.60	415
24	68	113	136	170	226	272	340	408	452	510	565	621	680	739	795	904	1020	1130	1242	1360	1478	1590	1.95	23.52	452
25	73.6	121	147	183	242	294	367	441	484	541	605	670	735	800	860	968	1101	1210	1340	1470	1600	1720	2.12	25.44	490
26	79.6	132	159	198	264	318	397	477	528	594	660	730	795	865	930	1056	1191	1320	1460	1590	1730	1860	2.30	27.60	531
27	86	143	172	215	286	344	430	516	572	645	715	785	860	930	1000	1144	1290	1430	1570	1720	1860	2000	2.48	29.76	572
28	92	153	184	230	306	368	460	552	612	690	765	845	920	1000	1075	1224	1380	1530	1690	1840	2000	2150	2.66	31.92	615
29	99	165	198	247	330	396	495	594	660	741	825	910	990	1075	1155	1320	1485	1650	1820	1980	2150	2310	2.85	34.20	660
30	106	176	212	265	352	424	530	636	704	795	880	970	1060	1150	1240	1408	1590	1760	1940	2120	2300	2480	3.06	36.72	707
31	113	188	226	287	376	452	565	678	752	851	940	1035	1130	1220	1315	1504	1695	1880	2070	2260	2440	2630	3.26	39.12	754

TABLE XXXIV—*Continued*

Ram Dia.	Working Pressure, P.S.I.																						Gals. per 1" Stroke	Gals. per Ft. Stroke	Area
	300	500	600	750	1000	1200	1500	1800	2000	2250	2500	2750	3000	3250	3500	4000	4500	5000	5500	6000	6500	7000			
	Capacity in Tons																								
32	120	202	240	302	404	480	605	720	808	906	1010	1108	1210	1300	1400	1616	1815	2020	2216	2420	2600	2800	3.47	41.64	804
33	128	213	256	320	426	512	640	768	852	960	1065	1175	1280	1380	1490	1704	1920	2130	2350	2560	2760	2880	3.70	44.40	855
34	136	226	272	340	452	544	680	816	904	1026	1130	1250	1360	1470	1585	1808	2040	2260	2500	2770	2940	3170	3.91	46.92	908
35	145	240	290	360	480	580	720	870	960	1080	1200	1320	1440	1560	1680	1920	2160	2400	2640	2880	3120	3360	4.16	49.96	962
36	152	253	304	380	506	608	760	912	1020	1140	1275	1388	1520	1650	1780	2024	2280	2530	2776	3040	3300	3560	4.38	52.50	1017
37	161	270	322	402	540	644	805	966	1080	1206	1350	1475	1610	1750	1885	2160	2415	2700	2950	3220	3500	3770	4.63	55.50	1075
38	170	283	340	425	566	680	850	1020	1140	1275	1415	1555	1700	1850	1985	2264	2550	2830	3110	3400	3700	3970	4.91	58.92	1134
39	179	298	358	447	596	716	895	1074	1192	1341	1490	1640	1790	1940	2090	2384	2685	2980	3280	3580	3880	4180	5.15	61.80	1194
40	188	313	376	470	626	752	940	1128	1252	1410	1565	1725	1880	2030	2195	2504	2820	3130	3450	3760	4060	4390	5.41	64.92	1256
41	198	330	396	495	660	792	990	1188	1320	1485	1650	1815	1980	2140	2300	2640	2970	3300	3630	3960	4280	4600	5.70	68.40	1320
42	208	346	416	520	692	832	1040	1248	1384	1560	1730	1900	2080	2250	2425	2768	3120	3460	3800	4160	4500	4850	6.00	72.00	1385
43	218	363	436	545	726	872	1090	1308	1452	1635	1815	2000	2180	2350	2535	2904	3270	3630	4000	4360	4720	5070	6.28	75.36	1452
44	226	380	452	570	760	904	1140	1356	1520	1710	1900	2087	2280	2470	2650	3040	3420	3800	4175	4560	4940	5300	6.57	78.84	1520
45	238	396	476	595	792	952	1190	1428	1584	1785	1980	2180	2380	2580	2775	3168	3470	3960	4360	4760	5160	5550	6.87	82.44	1590
46	250	416	500	625	832	1000	1250	1500	1664	1875	2080	2290	2500	2700	2900	3328	3750	4160	4580	5000	5400	5800	7.38	88.56	1662
47	260	433	520	650	866	1040	1308	1560	1732	1950	2165	2390	2600	2820	3025	3464	3900	4330	4780	5200	5640	6050	7.50	90.00	1735
48	271	451	542	677	902	1084	1355	1626	1804	2031	2255	2485	2710	2940	3150	3608	4065	4510	4980	5420	5880	6300	7.80	93.60	1809
49	283	471	576	706	942	1152	1412	1728	1884	2118	2355	2590	2825	3060	3300	3678	4236	4710	5180	5650	6120	6600	8.30	99.60	1885
50	295	490	590	735	980	1180	1470	1770	1960	2205	2450	2695	2940	3190	3425	3920	4310	4900	5390	5880	6380	6850	8.50	102.00	1963
51	307	511	614	767	1022	1228	1535	1842	2044	2301	2555	2810	3070	3310	3550	4088	4605	5110	5620	6140	6620	7100	8.75	105	2043
52	319	531	638	797	1062	1276	1595	1914	2124	2391	2655	2925	3190	3490	3705	4248	4785	5310	5850	6380	6900	7410	9.30	112	2120
53	330	551	660	827	1102	1320	1655	1980	2204	2481	2755	3035	3310	3590	3875	4408	4965	5510	6070	6620	7180	7750	9.55	115	2206
54	343	573	686	860	1146	1372	1720	2058	2292	2580	2865	3100	3440	3720	4000	4584	5160	5730	6300	6880	7440	8000	9.80	118	2290
55	358	593	716	890	1196	1432	1780	2148	2392	2670	2965	3265	3560	3860	4185	4784	5340	5980	6530	7120	7720	8310	10.21	123	2376
56	370	616	740	925	1232	1460	1850	2220	2464	2775	3080	3395	3700	4000	4310	4928	5550	6160	6790	7400	8000	8620	10.61	127	2453
57	382	637	764	960	1274	1528	1912	2292	2548	2880	3185	3500	3825	4140	4475	5096	5736	6370	7000	7850	8300	8950	11.00	132	2551
58	390	661	792	992	1322	1584	1985	2376	2644	2976	3305	3640	3990	4280	4625	5288	5955	6610	7280	7940	8600	9250	11.40	137	2642
59	410	683	820	1025	1366	1640	2050	2460	2732	3075	3415	3750	4100	4400	4775	5464	6150	6830	7500	8250	8880	9550	11.80	142	2734
60	425	708	850	1062	1416	1700	2125	2550	2832	3186	3540	3900	4250	4600	4900	5664	6375	7080	7800	8500	9200	9800	12.32	147	2827

Table XXXV

TABLE OF DECIMAL EQUIVALENTS OF EIGHTHS, SIXTEENTHS, THIRTY-SECONDS AND SIXTY-FOURTHS OF AN INCH

8ths	32ds	64ths	64ths—Cont.
1/8 = .125	1/32 = .03125	1/64 = .015625	33/64 = .515625
1/4 = .250	3/32 = .09375	3/64 = .046875	35/64 = .546875
3/8 = .375	5/32 = .15625	5/64 = .078125	37/64 = .578125
1/2 = .500	7/32 = .21875	7/64 = .109375	39/64 = .609375
5/8 = .625	9/32 = .28125	9/64 = .140625	41/64 = .640625
3/4 = .750	11/32 = .34375	11/64 = .171875	43/64 = .671875
7/8 = .875	13/32 = .40625	13/64 = .203125	45/64 = .703125
16ths	15/32 = .46875	15/64 = .234375	47/64 = .734375
1/16 = .0625	17/32 = .53125	17/64 = .265625	49/64 = .765625
3/16 = .1875	19/32 = .59375	19/64 = .296875	51/64 = .796875
5/16 = .3125	21/32 = .65625	21/64 = .328125	53/64 = .828125
7/16 = .4375	23/32 = .71875	23/64 = .359375	55/64 = .859375
9/16 = .5625	25/32 = .78125	25/64 = .390625	57/64 = .890625
11/16 = .6875	27/32 = .84375	27/64 = .421875	59/64 = .921875
13/16 = .8125	29/32 = .90625	29/64 = .453125	61/64 = .953125
15/16 = .9375	31/32 = .96875	31/64 = .484375	63/64 = .984375

Measure

To Change	To	Multiply by
Cubic feet	Cubic inches	1728
Cubic inches	Cubic feet	0.00058
Cubic feet	Gallons	7.480
Gallons	Cubic feet	0.1337
Cubic inches	Gallons	0.00433
Gallons	Cubic inches	231.
Imperial gals.	U.S. gallons	1.2009
U.S. gallons	Imperial gals.	0.8326
Feet	Inches	12
Inches	Feet	0.0833
Square feet	Square inches	144
Square inches	Square feet	0.00695
Long tons	Pounds	2240
Short tons	Pounds	2000
Long tons	Short tons	1.12

Weight

	Wt. Lbs.
1 cu. ft. of water	62.4 (@32F)
1 cu. inch of water	0.0361 (@32F)
1 gallon of water	8.33 (@32F)
1 cu. ft. of air	0.0763 (@60F-29.92" Hg)
1 cu. inch of steel	0.284
1 cu. ft. of brick (bldg.)	112–120
1 cu. ft. of brick (fire)	145–150
1 cu. ft. of coal	80–100
1 cu. ft. of coke	24–30
1 cu. ft. of concrete	120–140
1 cu. ft. of earth	70–120
1 cu. ft. of gravel	90–120
1 cu. ft. of wood	30–60

Pressure

To Change	To	Multiply by
Inches of water	Pounds per square inch	0.0361
Pounds per square inch	Inches of water	27.71
Feet of water	Pounds per square inch	0.4334
Pounds per square inch	Feet of water	2.310
Inches of mercury	Pounds per square inch	0.4914
Pounds per square inch	Inches of mercury	2.04
Atmospheres	Pounds per square inch	14.696
Pounds per square inch	Atmospheres	0.06804

Density

To Change	To	Multiply by
Pounds per cubic foot	Kilogram per cubic meter	16.0184
Kilogram per cubic meter	Pounds per cubic foot	0.06243

Power

To Change	To	Multiply by
Horsepower	Kilowatts	0.746
Kilowatts	Horsepower	1.3404
B.T.U.	Foot-pounds	778.3
Foot-pounds	B.T.U.	0.001285
B.T.U.	H.P. hours	0.0003927
H.P. hours	B.T.U.	2544.1
B.T.U.	Kw. hours	0.0002928
Kw. hours	B.T.U.	3412.75

APPENDIX II

PROBLEMS

1. What pressure would be required to blank a plain round disc 1 ft. in diameter from $\frac{1}{16}$-in. thick annealed aluminum (no shear on tools)? Ref.: Chart I, Table II formula 2.

2. How much energy is consumed in this operation, assuming ample clearance?

a. By Chart III and Table II?

b. By formula 3, assuming average pressure to be a half of the maximum pressure?

3. Would you select for this operation a non-geared press with 350-lb. flywheel, 30-in. diameter, running 150 r.p.m., or a similar size press geared 5: 1 and having a 250-lb. flywheel, 26-in. diameter, running 300 r.p.m. on the back shaft? Why? Ref.: Chart XI.

4. What shaft size in an inclinable press would you select for this job, allowing a safety margin of 100 per cent? Ref.: Chart X.

5. Referring to Fig. 44 *B*, if the perimeter of each punch is 4 in., the metal is hard rolled 0.40 C steel $\frac{1}{8}$ in. thick (Table II) and one punch is ground $\frac{1}{32}$ in. shorter than the other, what will the maximum shearing pressure be, and why? Assume ample clearance for a clean fracture. Ref.: Table II, cols. 3 and 4; Figs. 24 and 27 *A*; Chart I; formula 2.

6. In a power shear cutting the length of a 10-ft. sheet of quarter-inch steel plate specified as 0.20 C annealed steel with the upper shear blade having a slope of $\frac{1}{4}$ in. per ft., what is the shearing load:

a. By Chart II? Ref.: Figs. 28 and 56 *C*.

b. By formula 1? (Assume that average pressure is a third of maximum pressure.)

7. In Fig. 79*A* compute the length of blank required to produce the part shown, if its dimensions are: A and $C = 1$ in., $B = 1\frac{1}{2}$ in., both bends are through an angle of 45°, the inside radius of the bend is $r = \frac{1}{2}$ in., and the metal thickness $t = \frac{1}{4}$ in. Ref.: formula 4.

8. Compute the minimum pressure to bend and set a strip of steel $1\frac{1}{2}$ in. wide in the V-die shown in Fig. 80 *D* if the plan projected width of the coining bead on the punch is 0.200 in. and the yield point of metal of the temper required is 110,000 lb. per sq. in. Ref.: Chart IX; Fig. 191.

9. What will be the probable final wall thickness, around its greatest diameter, of a shell drawn to a diameter of 5.5 in. with a wall thickness of 0.050 in. and bulged to a diameter of 7 in.? Ref.: Fig. 94 *A* and *B*; formula 5.

10. Compute the minimum total pressure in tons on a plunger 3 in. in diameter (Fig. 97 *B*) to bulge the shell shown to a final state in which the diameter is 12 in.; the metal thickness is 0.080 in. and its yield point is 70,000 lb. per sq. in. Ref.: formula 8.

11. If a piece of copper tube of 3-in. outside diameter with ¼-in. wall is to be bulged by endwise pressure in a suitable die, and the yield point of the metal, as received, is 40,000 lb. per sq. in., what will be the least pressure required to do the job? Ref.: Fig. 103; formula 9.

12. In necking-in the top of a drawn shell from a mean diameter of 2 in. and a wall thickness 0.078 in. to mean diameter 0.800 in., about what will the wall thickness become? Ref.: Figs. 106 and 107; formula 10.

13. In the case just discussed, what would be the maximum pressure required for the first reduction, assuming an angle (a) of 45° and an elastic limit for the steel of 55,000 lb. per sq. in.? Ref.: formula 13.

14. Referring to Fig. 109 A and G, it is desired to pierce and burr up as high a flange as possible without fracturing the edge. The metal is 0.050 in. thick, and the outside diameter of the flange is to be 1½ in. What will be the diameter of the pierced hole and the height of the flange? Ref.: formulae 14 and 16.

15. In Figs. 125 and 126, if the "second draw" involved a 31 per cent reduction in diameter from the annealed state, compute the maximum wall stress at the end of the operation. Ref.: formula 18.

16. How much will any unit of area marked on the cylindrical surface of the above shell have been increased in length during that operation? Ref.: Figs. 18 and 125.

17. In Fig. 145, if the final shell is 2⅝ in. in diameter and 4 in. high, what are the approximate diameters of the blank and the several shells? Ref.: formula 25; Table XXV; Chart V.

18. Referring to Figs. 145 and 125, and assuming that the material is annealed 0.10 C steel in which internal fractures should appear after 55 per cent reduction, would you recommend annealing, and if so at what point or points in the series of operations?

19. Assuming S_1 and S_x as shown in Fig. 125, what would be the theoretical wall stress after the whole series of operations (Fig. 145), if there were no annealing? Ref.: formula 18.

20. Assuming 16-gauge metal with a theoretical yield point as received of 50,000 lb. per sq. in., what will be the drawing pressure for the first operation in Fig. 145? Take $C = 0.3$. Ref.: formula 22; problem 17.

21. What would be the load to pull the bottom out of this same shell? Take the nominal tensile strength from Fig. 19. Ref.: formula 21.

22. Neglecting friction, how much work would be done in the first draw in Fig. 145? Assume $C = 0.75$. Ref.: problems 17 and 20; formula 24; Table XXV.

23. If there has been no ironing at any point in the series of operations, what is the probable difference in thickness between the metal in the center of the bottom and at the top edge of the last shell in Fig. 145? Ref.: problems 17 and 20; formula 28; Chart VII.

24. If the bottom corner of the shell just mentioned has become 5 per cent thinner than the original metal thickness, what would be the maximum ironing load to give uniform wall thickness all the way up, allowing 20 per cent for friction? Assume a yield point in the final state of 75,000 lb. per sq. in. Ref.: formula 30; Chart VIII.

25. As the metal near the bottom of the above shell is in practically the annealed state (yield point 50,000 lb. per sq. in.), check the strength of the shell through that section and advise if the above is practical as a single operation without annealing? Ref.: formula 21; Chart VI.

26. In Fig. 156 the dimensions of the first-operation shell are: length 7 in., width 4 in., depth 3 in., corner radius 1 in., and material 18 gauge (0.050 in.), 0.10 C steel

with an initial theoretical yield point of 50,000 lb. per sq. in. Assume $C_1 = 1$ and $C_2 = 0.3$, and compute the drawing pressure required. Ref.: formula 32.

27. If the periphery of the blank for the above shell is 38 in., what is the blanking load, without shear on the tools? Ref.: Table II, formula 2, Chart I.

28. Assuming an 8-in. press stroke, at approximately what speed should the press run? Ref.: problem 26; Table XVI; Fig. 177; Chart XII or Chart XIII.

29. Making a 50 per cent allowance to take care of emergencies, select a suitable crankshaft size for the press for problems 27 and 28 (nearest half inch). $C = 2.2$. Ref.: Table XXIV; Chart X.

30. If the blank-holding pressure is equal to a third of the drawing pressure and the job is to be done in a combination die so that this pressure offers approximately constant resistance throughout the drawing stroke, compute the energy required to produce the shell described in problem 26. Neglect blanking and friction. $C = 0.80$. Ref.: formula 24.

31. The press which we have been selecting in the last four problems is built in three ways: non-geared, with a 50-in. diameter, 1300-lb. flywheel; single-geared, ratio 7½ : 1 with a 42-in. diameter, 900-lb. flywheel; and double-geared, ratio 15 : 1 with a 40-in. diameter, 800-lb. flywheel. Compute the energy available in each case under intermittent operating conditions (20 per cent slow-down), and select the proper drive. Ref.: formula 42 ($\times$ 2); Chart XI; problems 28 and 30.

32. In drawing or stretching a casket lid 6 ft. by 2 ft. from 0.034-in. copper-bearing steel there is a flange which is used for blank-holding and is later trimmed and then turned up and in. The flange and the lid surfaces meet at an angle of, say, 36°, about as shown in Fig. 142. What is the drawing load, assuming the elastic limit of the metal at 45,000 lb. per sq. in.? Ref.: formula 33.

33. A small lever in Fig. 190 has a 1-in. diameter boss at one end and one of 1½-in. diameter at the other end. These are to be squeezed to size from approximately $^{11}/_{16}$ in. thick to 0.625 in. ± 0.001. This tolerance requires the use of size blocks or distance pieces which may be assumed to take half of the load. If the yield point of the metal as forged is about 130,000 lb. per sq. in., what total pressure will be required? Ref.: Table IX; formula 41.

34. If the area of part j in Fig. 209 is 0.85 sq. in. exclusive of the bosses after swaging to 60 per cent of the original metal thickness, and the material is a 0.20 C steel with a yield point as received (S_1) of 90,000 lb. per sq. in. and a rate of strain-hardening (S_x) of 160,000, what pressure will be required? Ref.: Fig. 122; formulae 18 and 41.

35. Select a suitable press (shaft) size for the above job, allowing 100 per cent overload margin and using the eccentric type shaft ($C = 4.3$). Ref.: Chart X.

36. What final tonnage will be required to produce a free-flowing beta brass forging with a plan projected area including flash of 9 sq. in. at a temperature of 1500° F. and at about 1170°? Ref.: Fig. 133; formula 41; Chart IX.

ANSWERS

1. 9.4 tons. **2a.** 0.41 in.-ton. **2b.** 0.29 in.-ton. **3.** The non-geared press, because it has ample energy available and operates faster. **4.** Approximately 2½-in. shaft. **5.** 19.5 tons. One punch has finished shearing before the other one reaches the metal. **6a.** 26.4 tons. **6b.** 22 tons. **7.** 4.443 in. **8.** 16.5 tons. **9.** 0.044 in. **10.** 3.3 tons. **11.** 86,500 lb. **12.** 0.123 in. **13.** 19,100 lb. **14.** 1.07 in. **15.** 68,600 lb. per sq. in. **16.** 42 per cent. **17.** 6.99 in., 4.19 in., 3.44 in., 2.94 in., 2.63 in. **18.** One anneal after first or second draw. **19.** 87,400 lb. per sq. in. **20.** 39,700 lb. **21.** 45,400 lb. **22.** 26.8 in.-tons. **23.** 0.0394 in. **24.** 29,680 lb. **25.** 24,800 lb. No. **26.** 26,200 lb. **27.** 66,500 lb. **28.** 24 SPM. **29.** 5 in. **30.** 89,080 in.-lb. or 44.5 in.-tons. **31.** 0.77 in.-ton, 21 in.-tons, 68 in.-tons. The double-geared drive is required. **32.** 173,000 lb. **33.** 332 tons. **34.** 50.15 tons. **35.** 5 in. **36.** 45 tons and 112.5 tons.

INDEX